Overview of BARC facilities and research activities in nuclear physics

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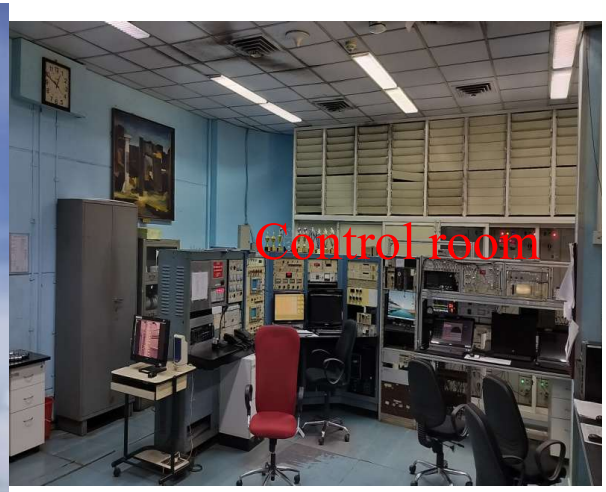
Outline

- Accelerator based facilities
  - ❑ BARC-TIFR Pelletron-Linac facility
    - ➢ Experiments on fission
    - ➢ Experiments using charged particle detector array
    - ➢ Measurement on surrogate reactions
    - ➢ Measurement on Nuclear Level density
  - ❑ FOTIA, BARC
    - ➢ Experiments on fission gated gamma measurement
    - ➢ PIGE Experiments
- Reactor based facilities
  - ❑ ISMRAN (Indian Scintillation Matrix for Reactor Anti-neutrino Research)
  - ❑ DURGA (Dhruva Utilization in Research using Gamma Array)
- Summary

BARC-TIFR Pelletron-Linac facility

Accelerator & Experimental Halls



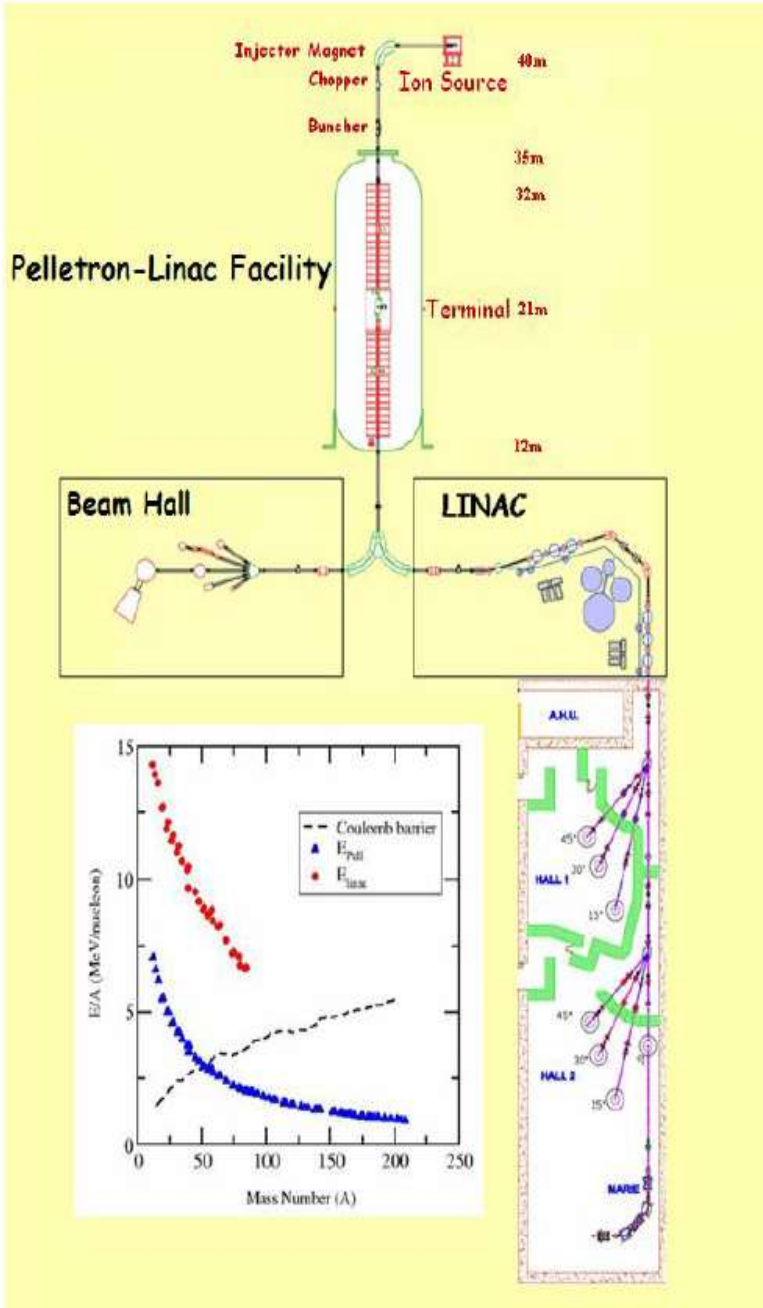
Beam: A<50

Energy: < 15 MeV/nucleon

Current: nA-μA

Experimental Halls: 3

Active beam-lines: ~8

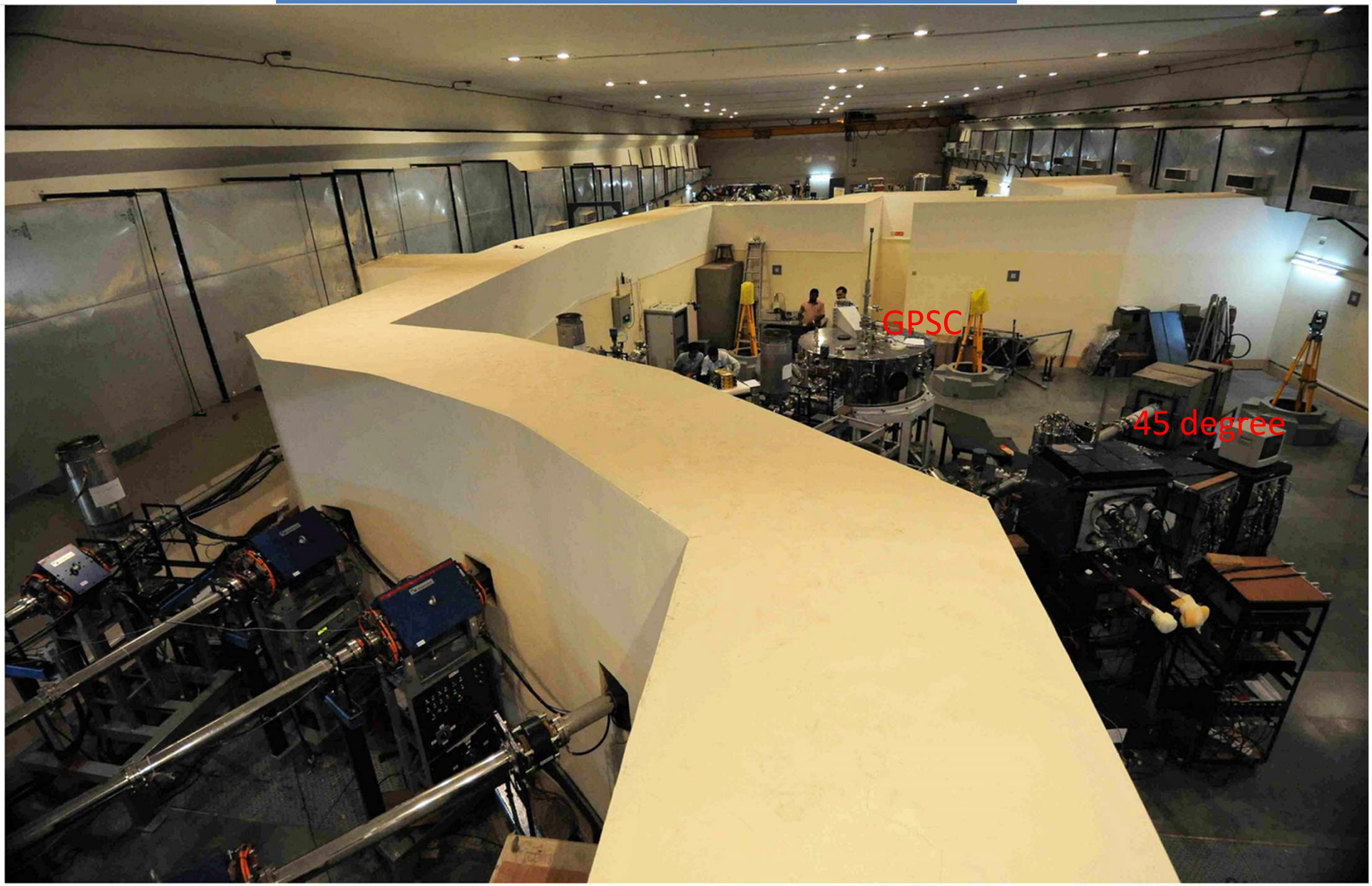


BARC-TIFR Pelletron-Linac facility

GPSC, CASCADE Hall

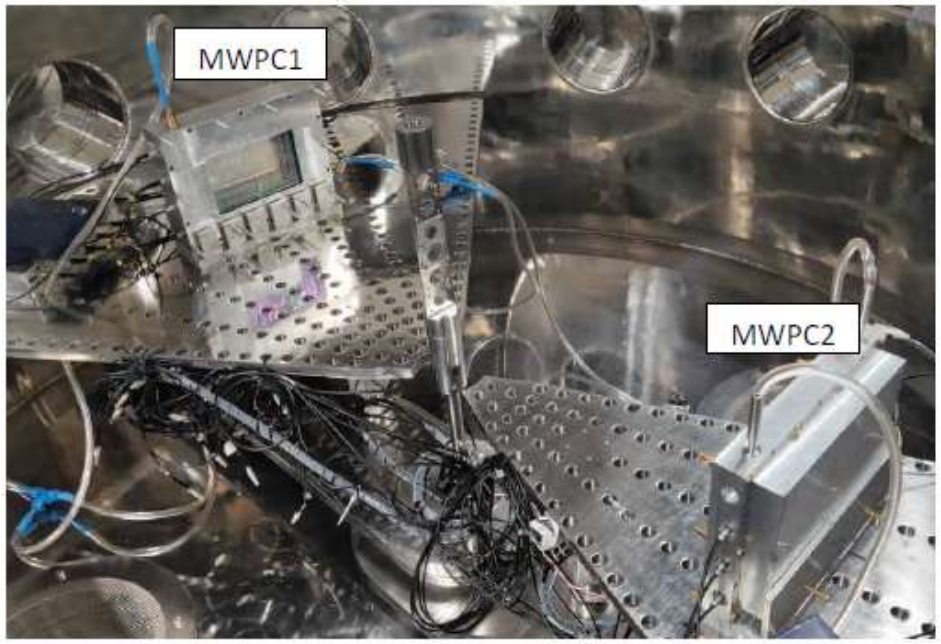
BARC-TIFR Pelletron-Linac facility

GPSC, LINAC-HALL-1



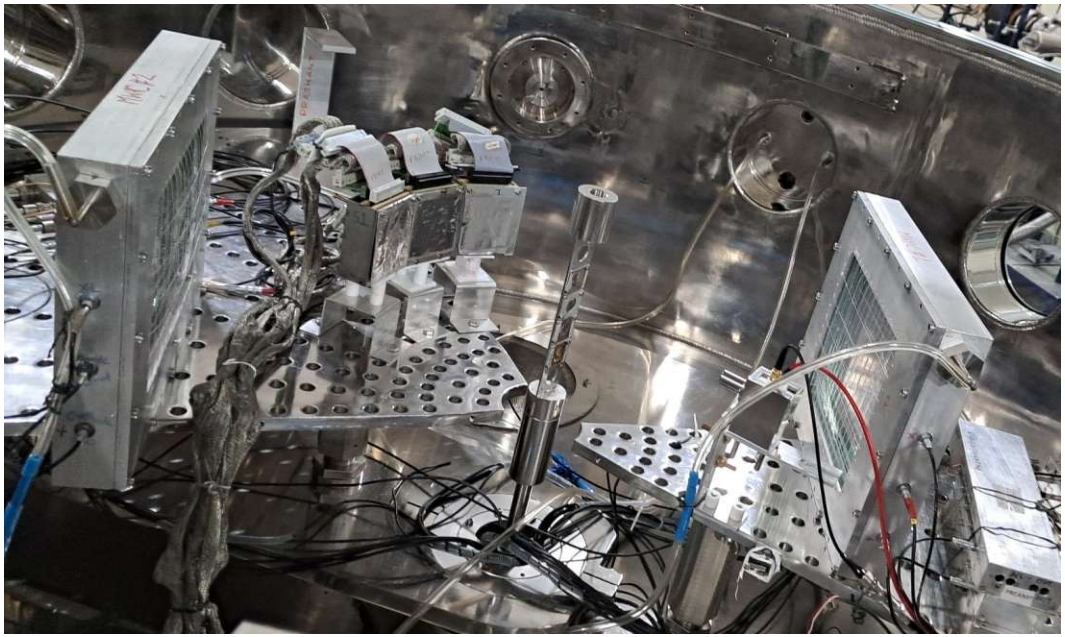
Fission experiments

GPSC, LINAC-HALL-1 (30 degree beam line)



Old –detectors: dimension (12.5 X 7.5 cm)

A. Pal et al. JINST 15, P02008 (2020)



New–detectors: dimension (22cm X 16 cm)

A. Pal et al. to be communicated

- Beam energy: ~ 0.9-1.4 V_B
- Target thickness ~100μg/cm^2
- Measure time of flight w.r.t pulsed beam
- Obtain velocity of fragments
- Apply momentum Conservation equation:

$$m_1 = v_{2cm} * m_{cn} / (v_{1cm} + v_{2cm})$$

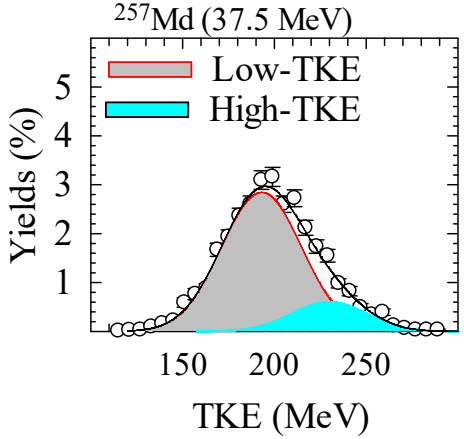
$$TKE = 0.5 * (m_1 v_{1cm}^2 + m_2 v_{2cm}^2)$$

Fission experiments

GPSC, LINAC-HALL-1 (30 degree beam line)

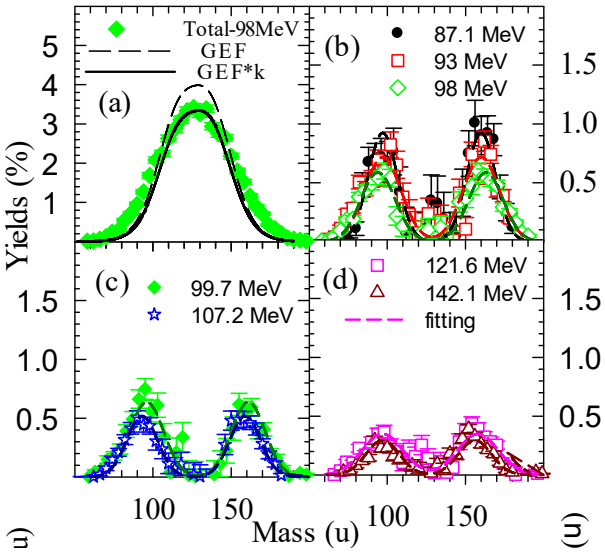
Fusion-fission

Study of fission modes



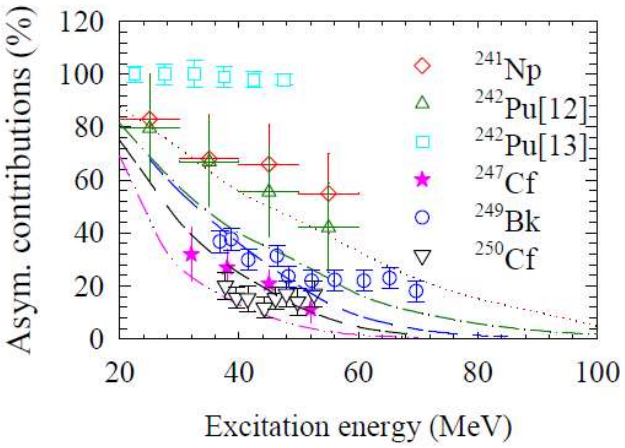
A.Pal et al. PRC 104, L031602 (2021)

Shell effect in slow quasi-fission



A. Pal et al. PRC 110, 034601 (2024)

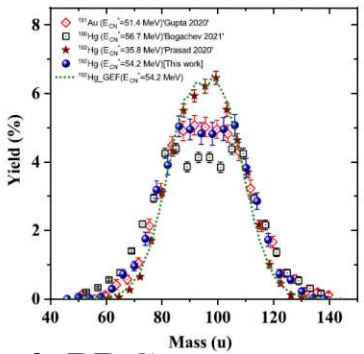
Role of multichance fission



S.Santra, **A. Pal** et al. Phys. Rev. C 107, L061601(2023)

Fission studies for pre-actinide nuclei:

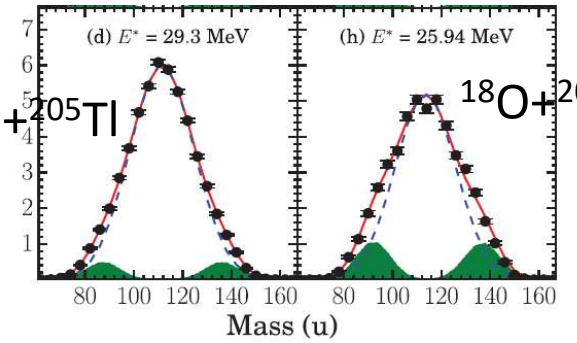
^{32}S+^{162}Gd →^{192}Hg



R. Kumar et al. PRC **107, 034614** (2023)

^{18}O+^{205}Tl

^{18}O+^{209}Bi



Reddy, **A. Pal** et al. PRC **110, 014622 (2024)**

^{32}S+^{144}Sm
T. Nag et. al. PRC (2021)

^{7}Li+^{203}Tl
S. Dhuri et. al. PRC (2022)

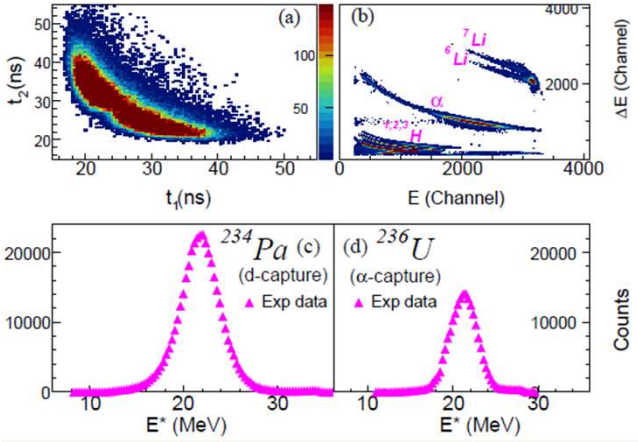
^{37}Cl+^{203}Tl ^{16}O+^{175}Lu
S. Gupta et. al. PLB (2023)

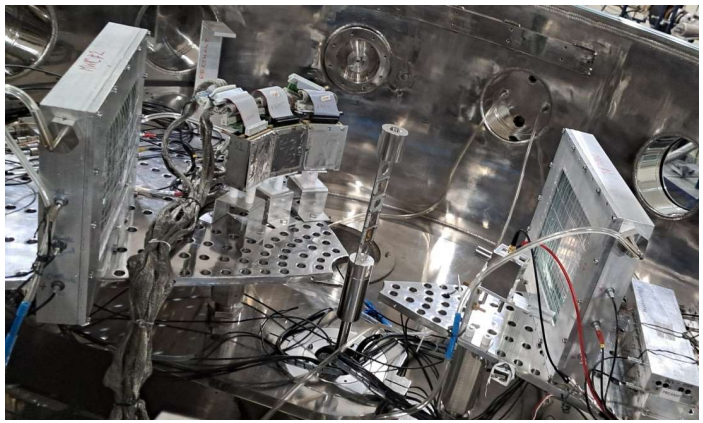
Fission experiments

GPSC, LINAC-HALL-1 (30 degree beam line)

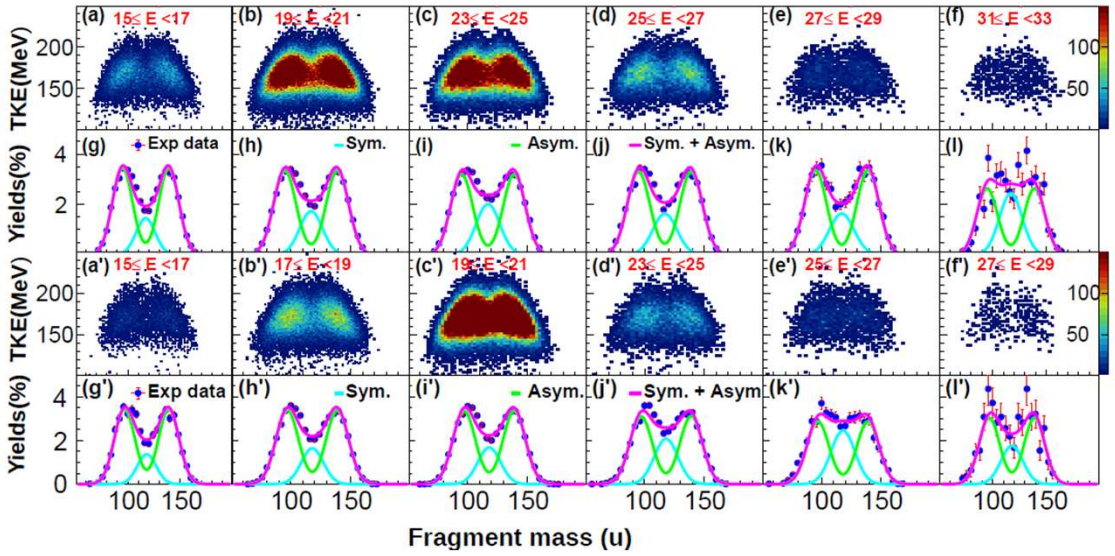
Transfer induced fission

Raw-data

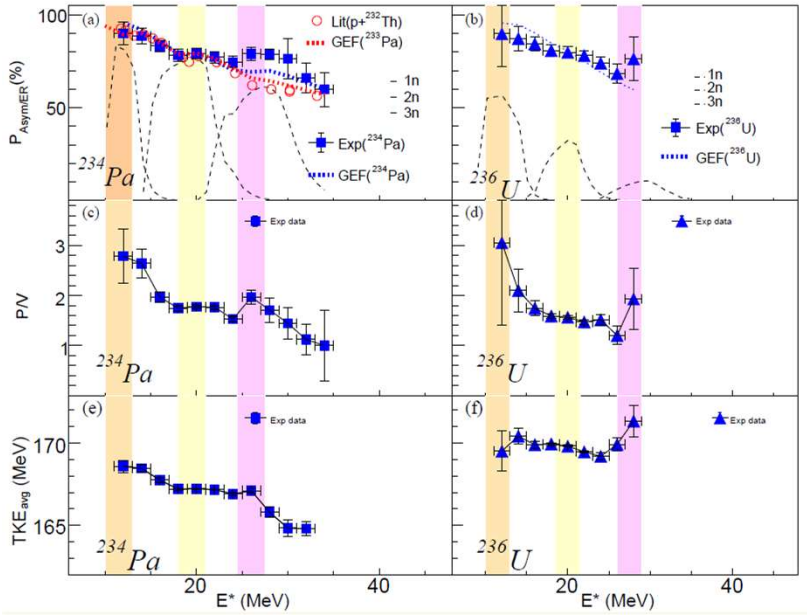




Mass-TKE distributions



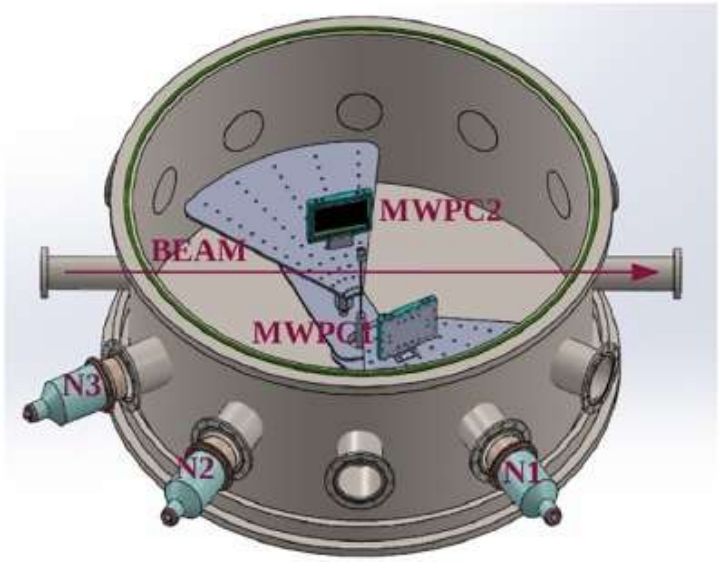
Multi-chance fission effect

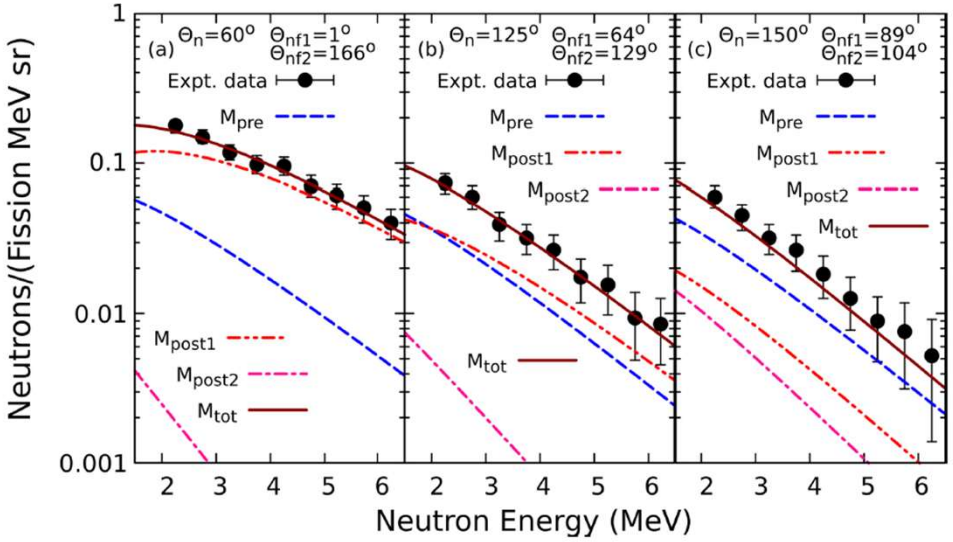


Saumya Sahu, A. Pal et al. (to be submitted)

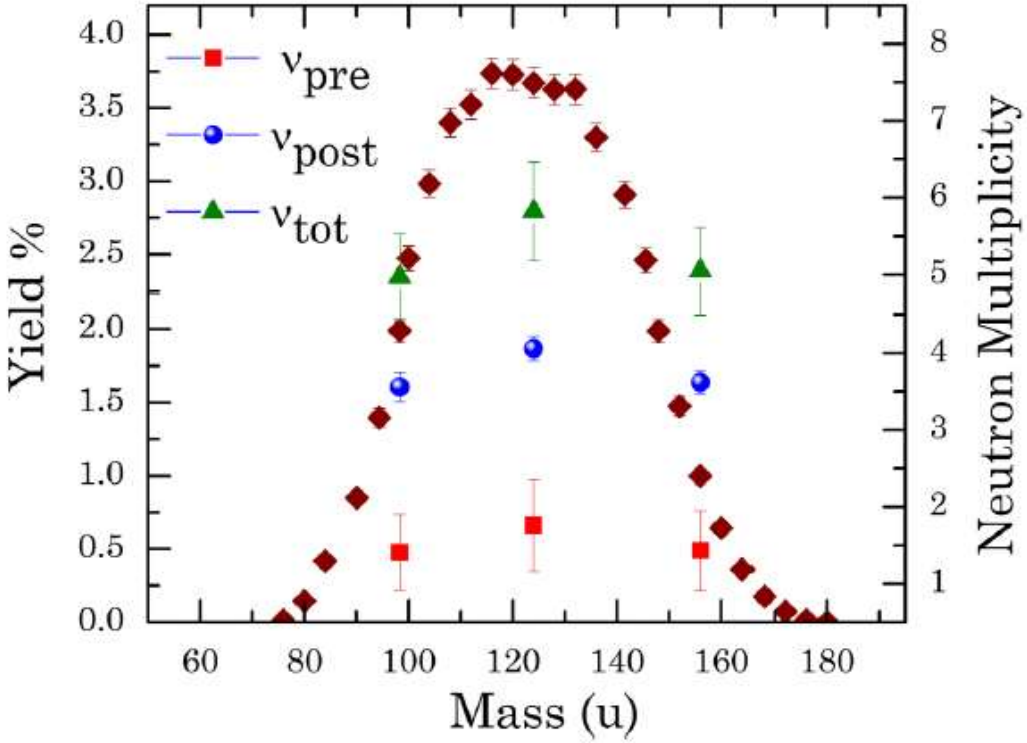
Fission experiments

GPSC, LINAC-HALL-1 (30 degree beam line)





Fission-neutron coincidence experiments

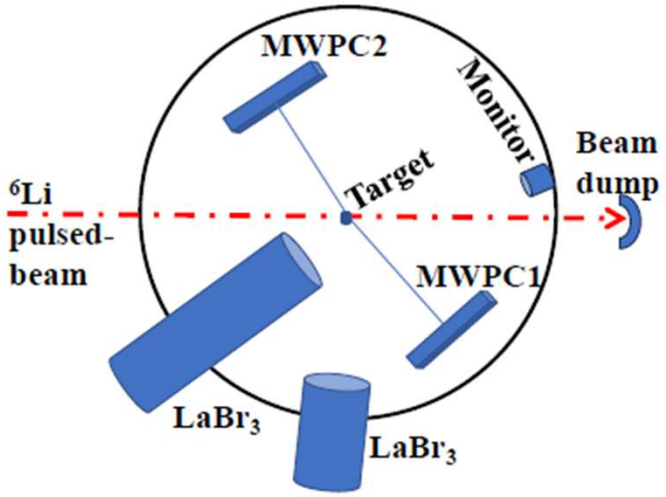


Mass-gated neutron multiplicity measurement

P.N.Patil et al. Phys. Rev. C 110,064602(2024)

Fission experiments

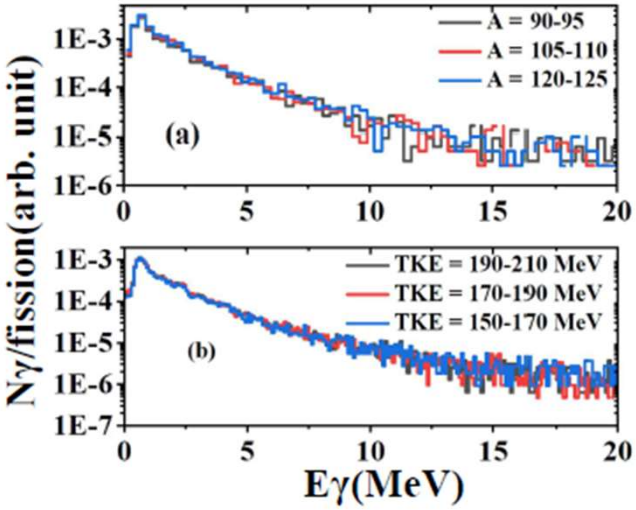
GPSC, LINAC-HALL-1 (30 degree beam line)

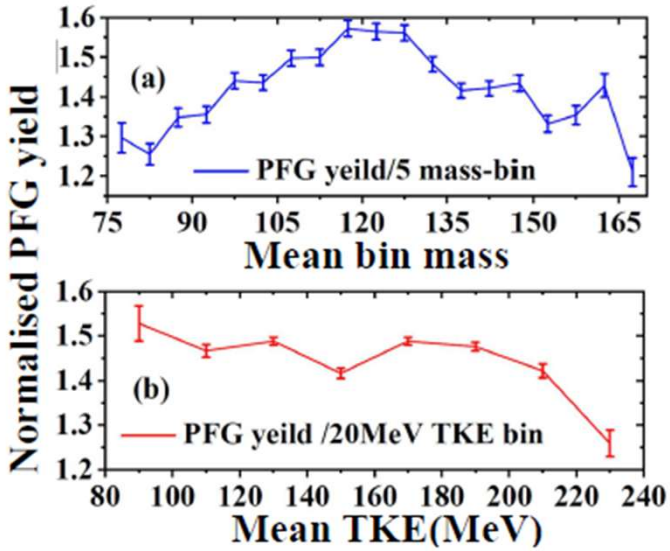


Mass-gated gamma multiplicity measurement

S. Samanta, A. Pal et. al. DAE-Symp on Nucl. Phys.(2024)

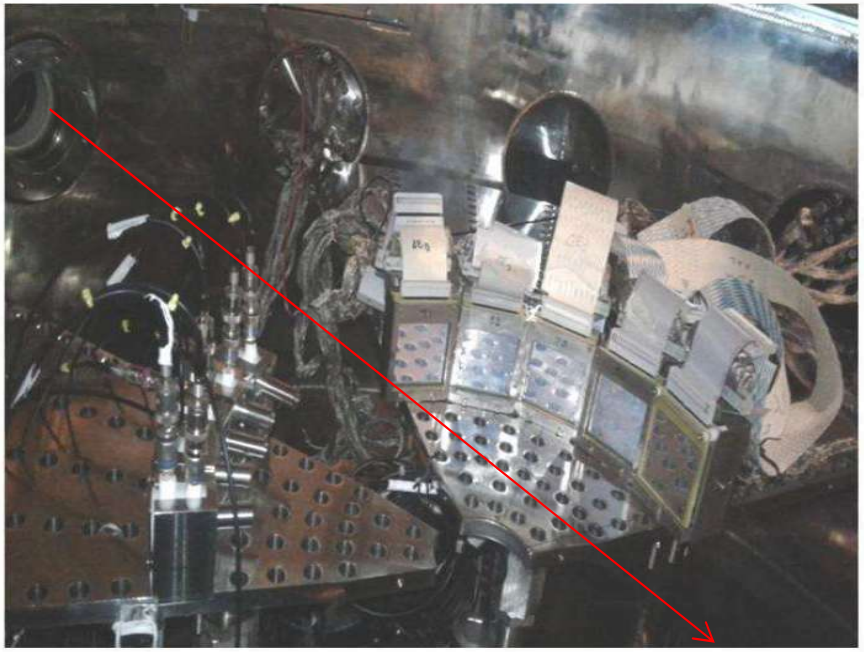
Fission-gamma coincidence experiments

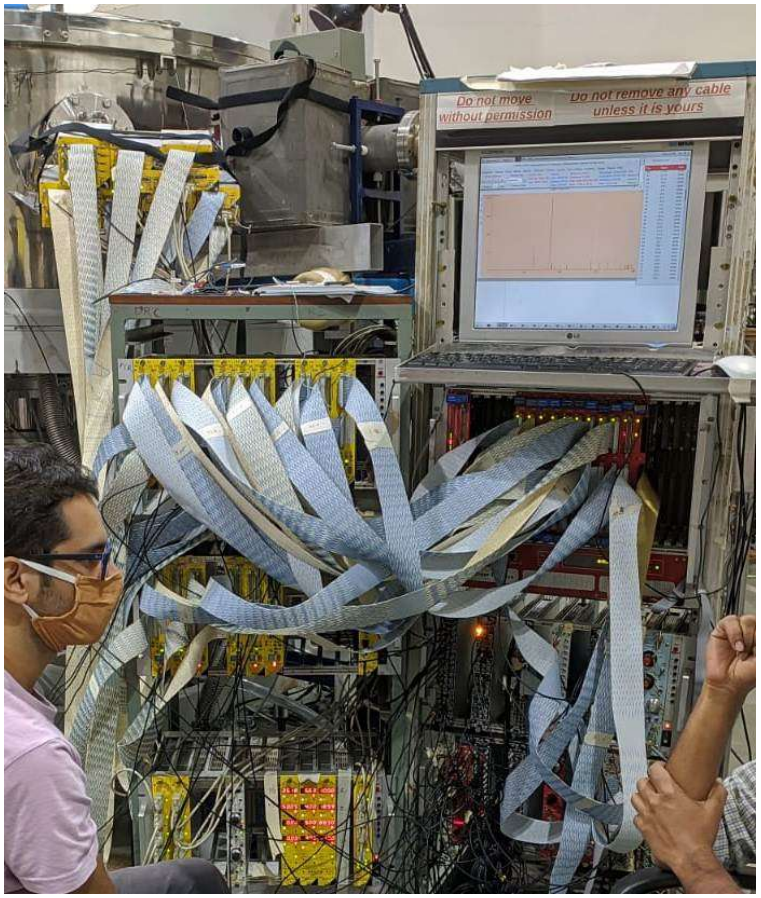




Experiments on breakup of weakly bound nuclei

GPSC, LINAC-HALL-1 (30 degree beam line)





Array of silicon strip detectors with ~100 deg angular coverage at BARC-TIFR Pelletron –Linac facility

No. of parameters

→ Energy signal: 240

→ Timing signal: 80

Bias voltage: 5-200 Volts

Pulse height of energy signals: <8 V

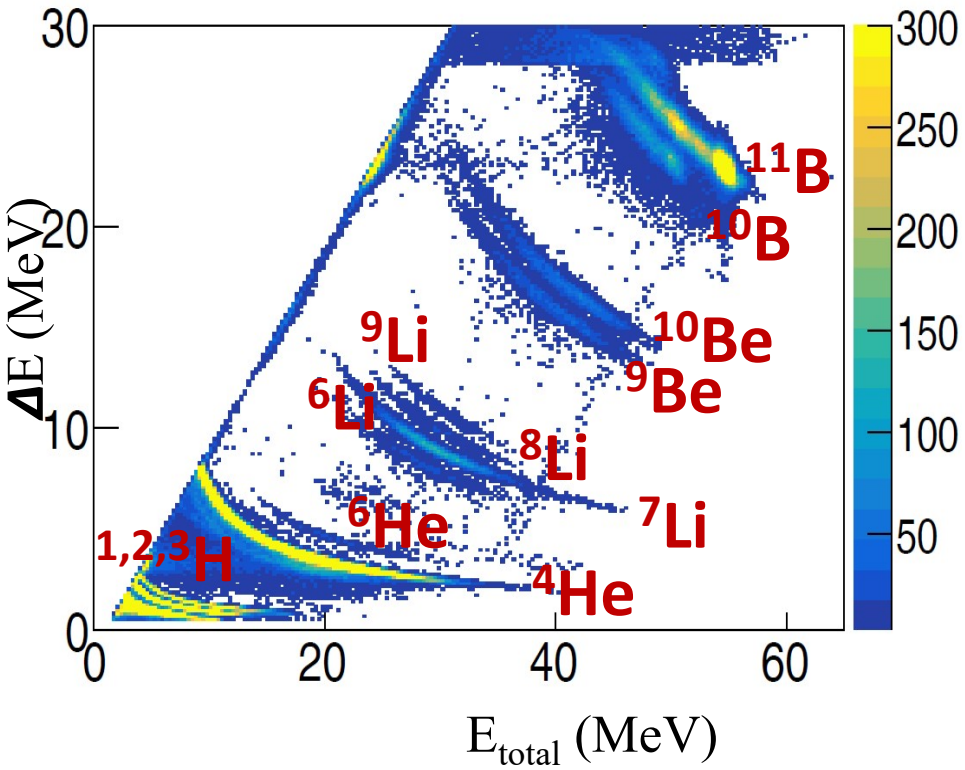
Dead time~ < 5 % at

event rate 5KHz

Experiments on breakup of weakly bound nuclei

GPSC, LINAC-HALL-1 (30 degree beam line)

→Important to understand structure of light nuclei, reaction dynamics and nuclear astrophysics



➢ Coincident particles are identified from the 2D PID plot.

➢ Relative energy between the fragments are calculated using the following relation

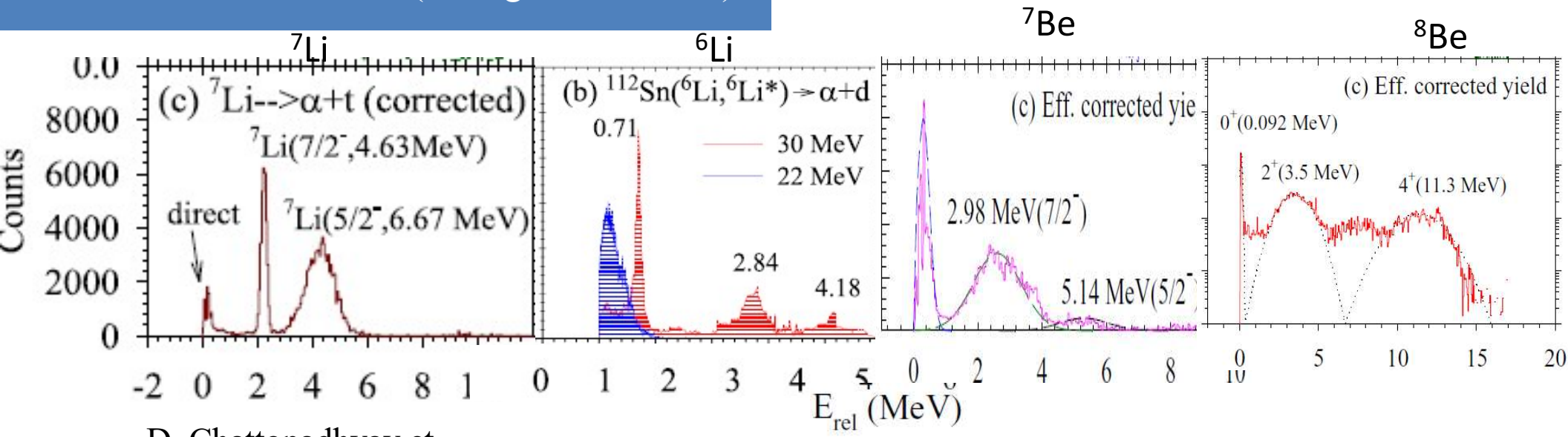
$$E_{relative}=0.5*\mu*(v_1-v_2)^2$$

(μ=reduced mass; v1,v2→measured velocities)

➢ Various kinds of 2D correlation plots (E_1 Vs. E_2, $E_{relative}$ Vs. E_2, $E_{relative}$ vs. Q) are made to ensure real breakup events, to identify resonance breakup states

Experiments on breakup of weakly bound nuclei

GPSC, LINAC-HALL-1 (30 degree beam line)

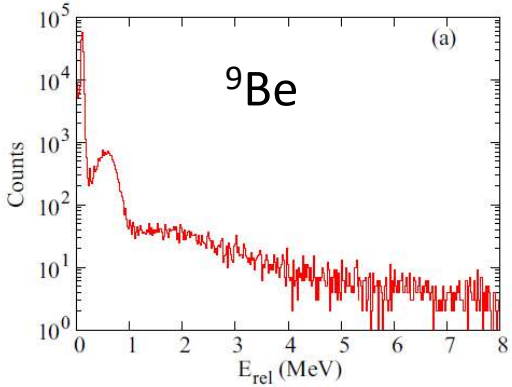


D. Chattopadhyay et al. Phys. Rev. C **97, 051601(R) (2018)**

D. Chattopadhyay et al. Phys. Rev. C 94,061602 (R)(2016)

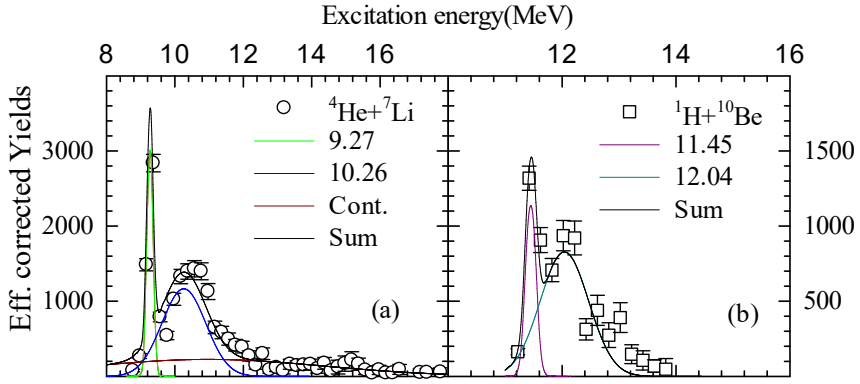
D. Chattopadhyay et al. Phys. Rev. C **102, 021601(R) (2020)**

D. Chattopadhyay et al. Phys. Rev. C 98,014609(2018)



T. Singh et al. Phys. Rev. C **111, 054615 (2025)**

^{11}B

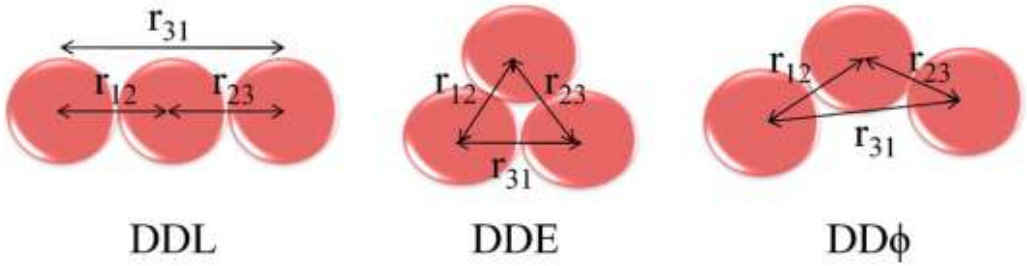


A. Pal et al. DAE-Symp. (2024)

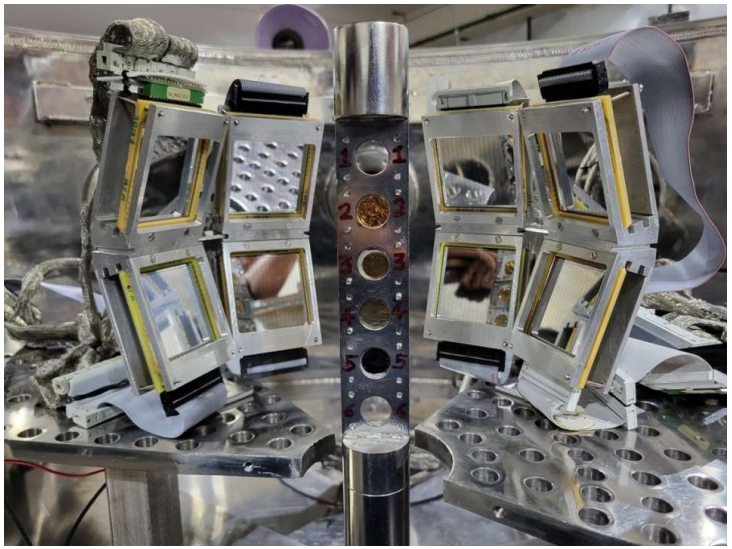
Experiments on Hoyle state

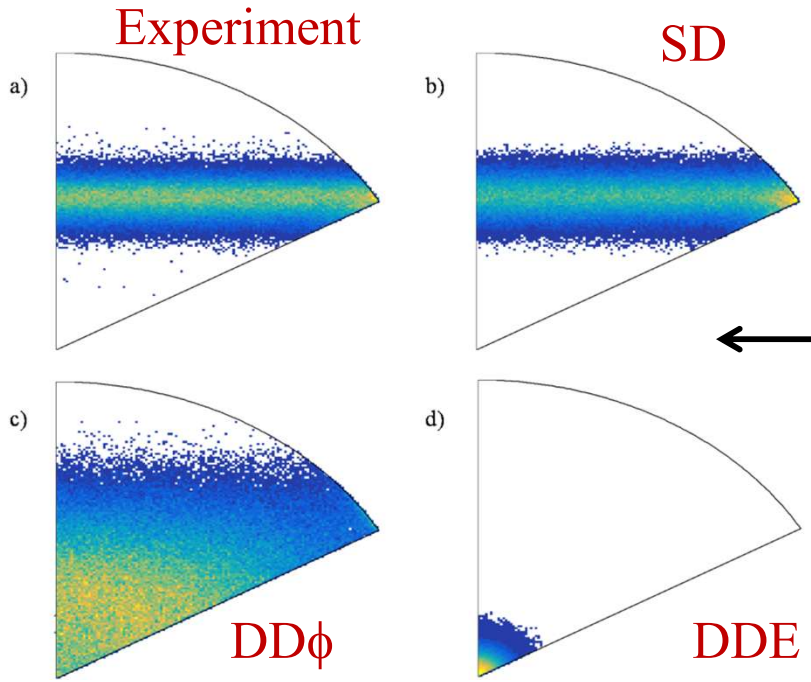
GPSC, LINAC-HALL-1 (30 degree beam line)

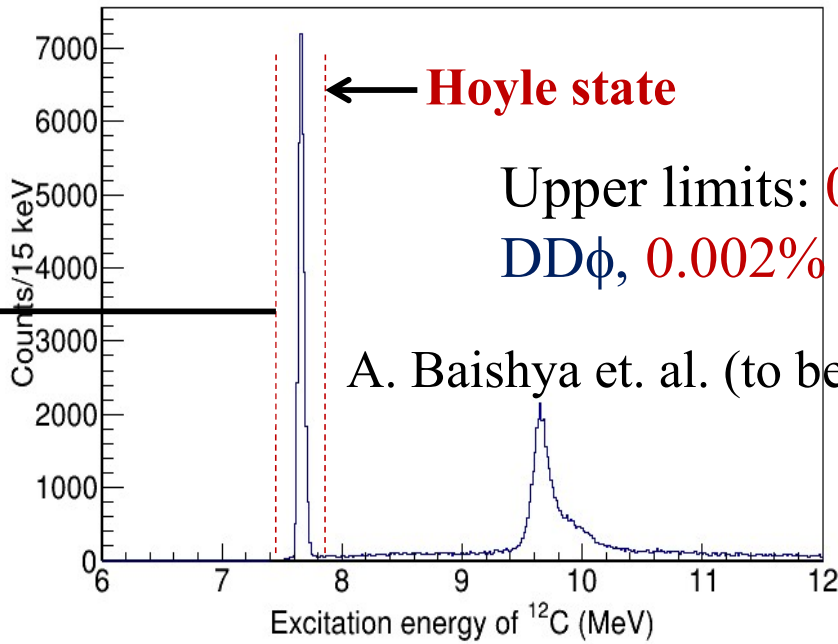
Direct 3α-decay of the Hoyle state



Reaction: $^{12}C+^{12}C$







Upper limits: 0.018% for DDϕ, 0.002% for DDE

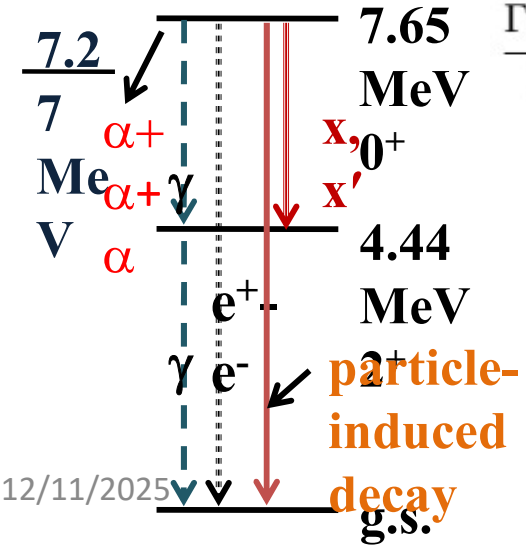
A. Baishya et. al. (to be submitted)

Experiments on Hoyle state

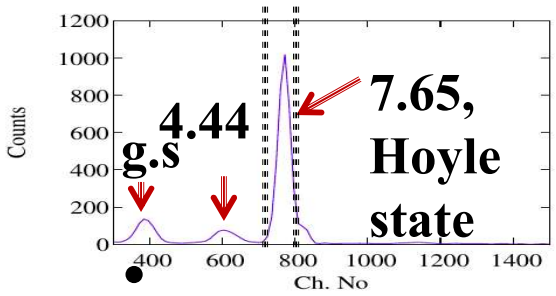
15 deg beam line, Cascade Hall

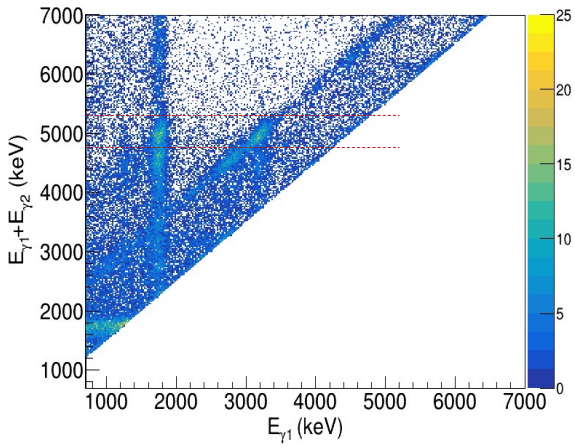
Reaction: p+^{12}C

Experimental Setup, i) Charged particle detectors (Si-strips), ii) γ detectors, BGO, total 38



$$\frac{\Gamma_\gamma^{7.65}}{\Gamma} = \frac{N_{020}^{7.65}}{N_{\text{singles}}^{7.65} \times \epsilon_{3.21} \times \epsilon_{4.44} \times W_{020}}$$



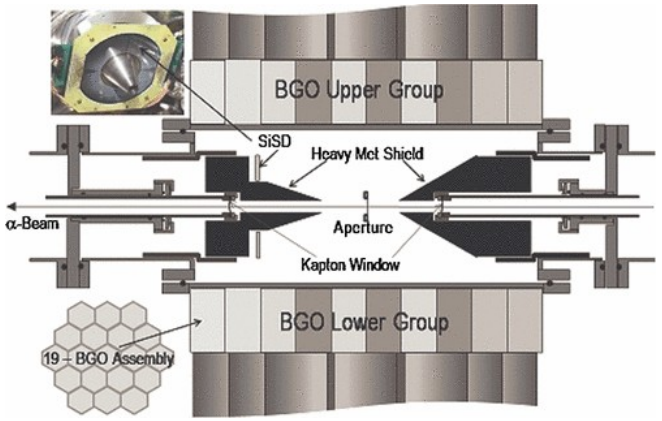


Energy loss of inelastically scattered protons in ΔE

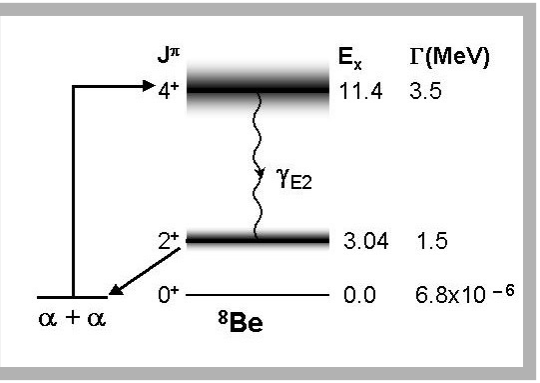
Experiments on transition strength measurement of ^{8}Be

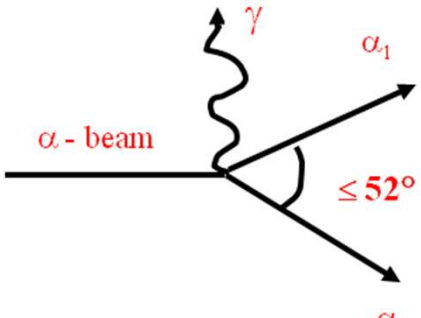
15 deg beam line, Cascade Hall

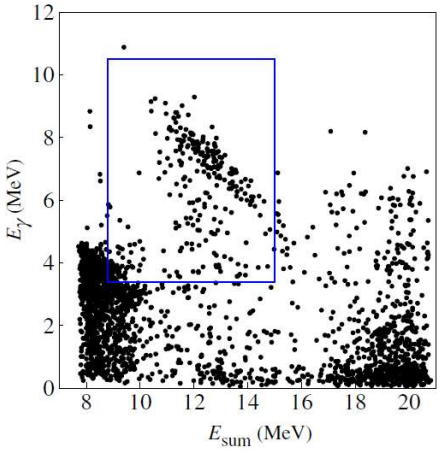
Reaction: ^{4}He+^{4}He

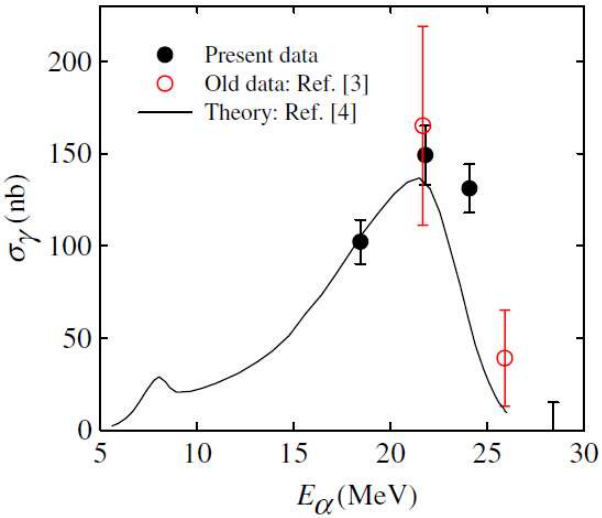


Datar et. al. Phys. Rev. Lett. 111, 062502 (2013)



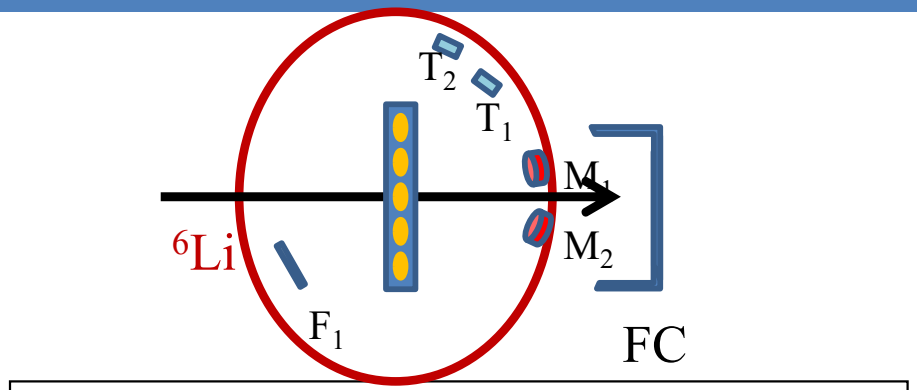


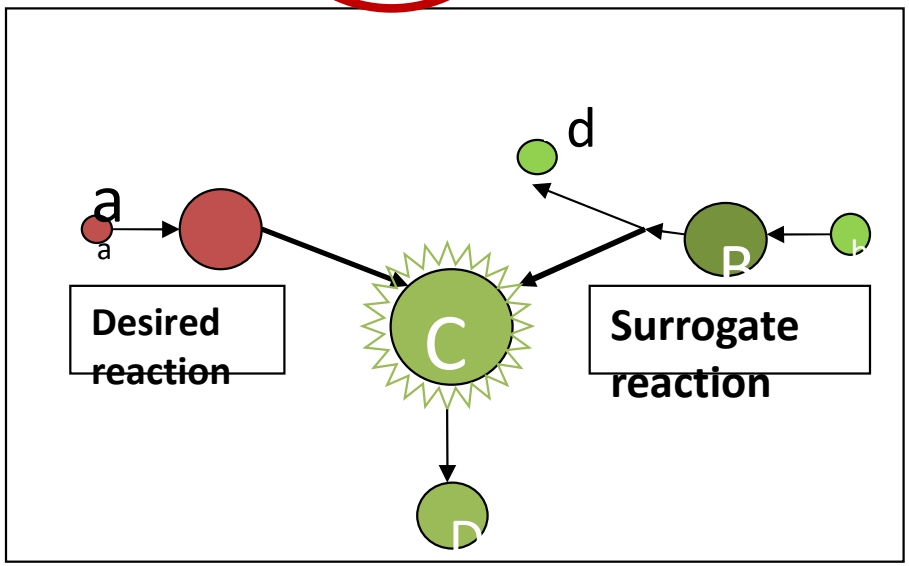




Experiments on surrogate reactions

GPSC, LINAC-HALL-1 (30 degree beam line)

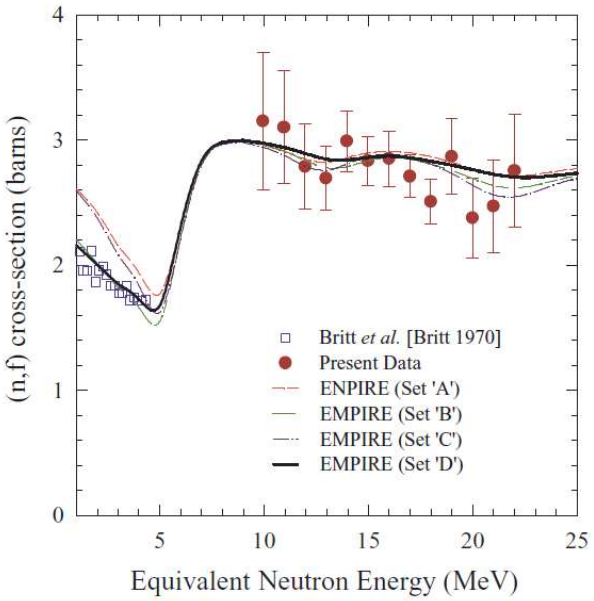




$$\frac{\sigma(^{236}Np(n,f)(E_x))}{\sigma(^{238}Pu(n,f)(E_x))} = \frac{\sigma^{^{237}Np}(E_x)}{\sigma^{^{239}Pu}(E_x)} \frac{N_{\alpha-f}}{N_\alpha} \frac{N_d}{N_{d-f}}$$

Important for Generation-IV reactors

^{236}Np(n,f) cross-section



A. Pal et al. PRC 91, 054618 (2015)

^{233}Pa(n,f)

Nayak et al. PRC 78, 061602 (2008)

^{239,240}Np(n,f)

Desai et al. PRC 88,014613 (2013)

^{234}Pa(n,f)

Desai et al. PRC 89, 024606 (2014)

Experiments on surrogate reactions

GPSC, LINAC-HALL-1/GPSC, Cascade Hall

Measurement of reaction cross-sections critical to Fusion reactors

D + T → n (14.1 MeV) + α (3.5 MeV)

Element	%age
Cr	16-18%
Fe	65-72%
Ni	10-14%
Mn	2-3%

Transmutation reactions

Radio Nuclie	Half life (Year)
^{53}Mn	3.74E+6
^{55}Fe	2.73
^{60}Fe	1.5E+6
^{60}Co	5.27
^{59}Ni	7.6E+4
^{63}Ni	100.1

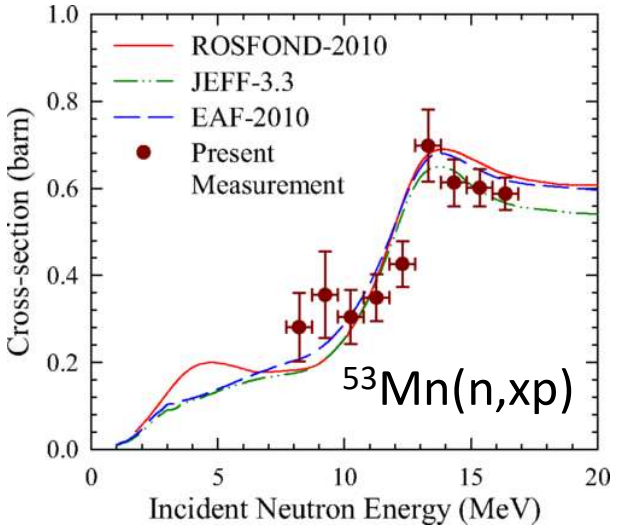
(n,xp) (n,xα)

Hydrogen **Helium**

Direct measurements Possible

(n,xp) (n,xα)

Hydrogen **Helium**



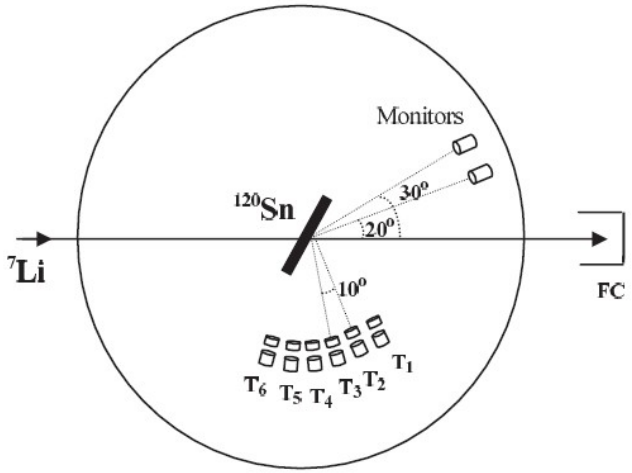
Phys. Rev. C **100**, 054613 (2019)
Phys. Rev. C **106**, 034609 (2022)
Eur. Phys. J. A **59**, 187 (2023)
Jour. Phys. G **51**, 125102 (2024)
Phys. Lett. B **848**, 138381 (2024)

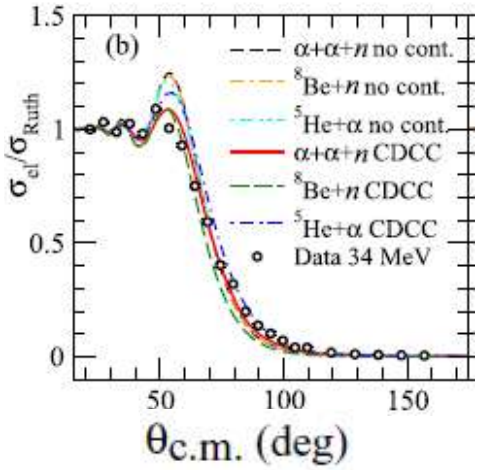
✓Gas production leads to **swelling** and **embrittlement** of structural material.

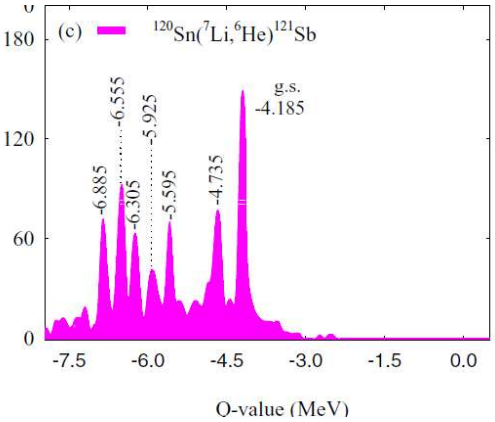
✓ (n,xp) & (n,xα) cross-section data have a critical importance for safety and design analysis of a fusion reactor .

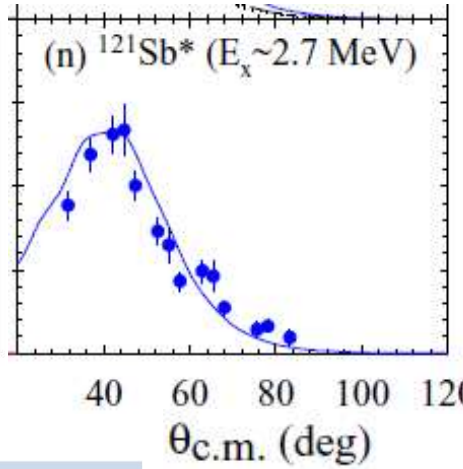
Experiments on elastic-inelastic scattering and transfer reaction

GPSC, CASCADE Hall/GPSC, Hall1









→Structural informations on target/projectile

^{9}Be→ A. Kundu et. al., Phys. Lett. B 864,139441 (2025)

^{7}Li→ A. Kundu et. al., Phys. Rev. C **95, 034615 (2017)**

^{9}Be→ H. Kumawat et. al., Phys. Rev. C **106, 024602 (2022)**

^{11}B→ A. Pal et. al., DAE Symp on Nucl. Phys **(2025)**

→Understanding cross-sections using TDHF calculations

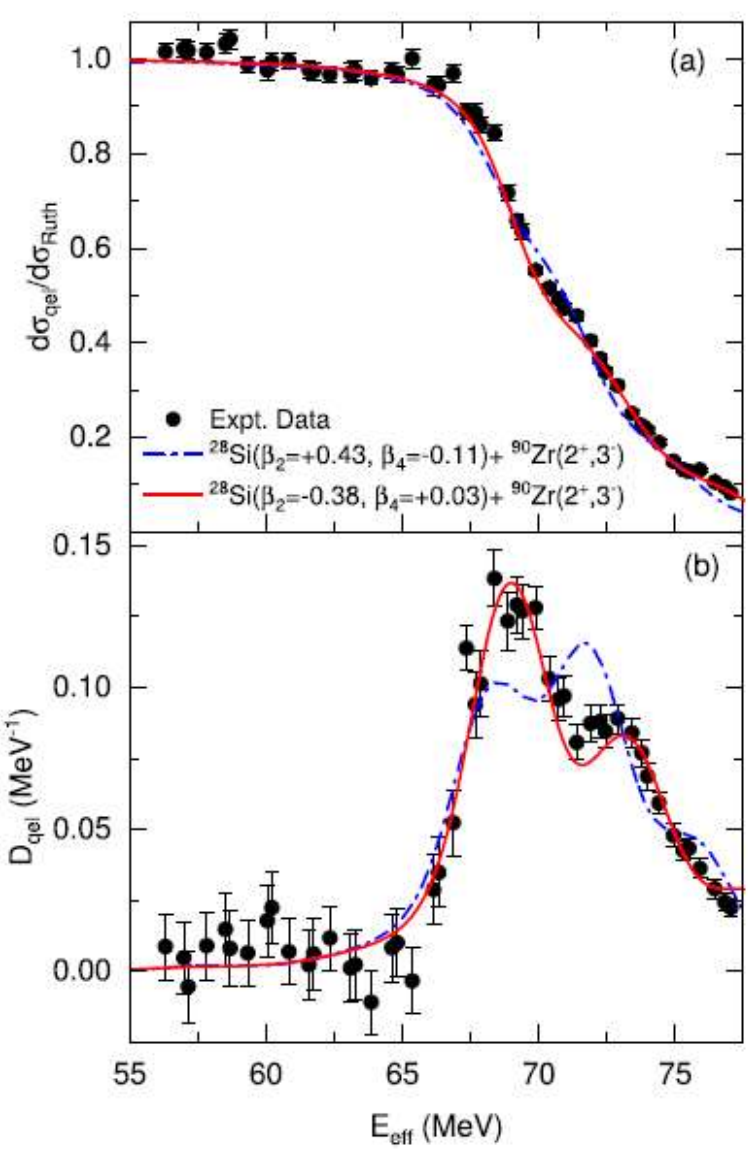
^{16}O→ B.J.Roy et. al., Phys. Rev. C **105, 044611 (2022)**

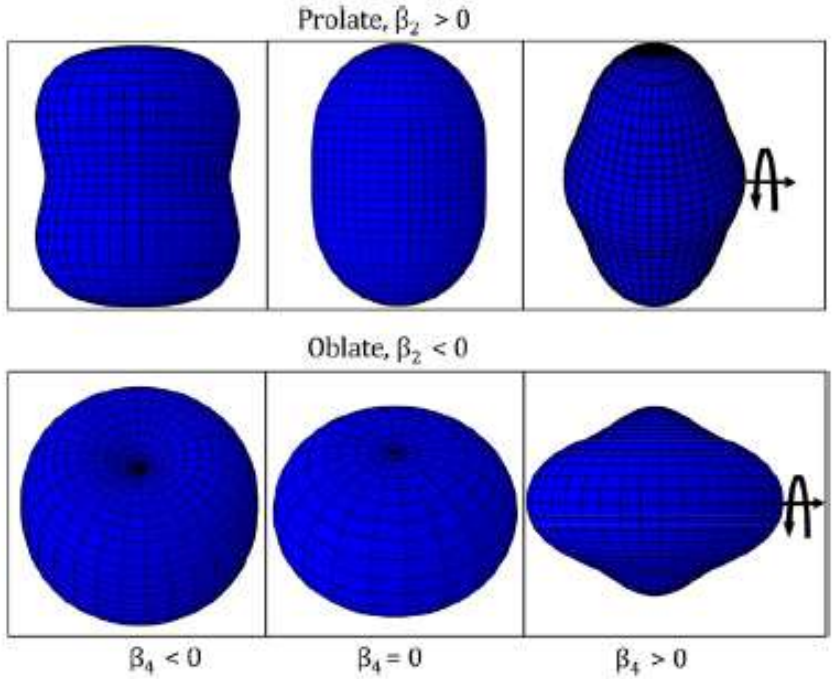
^{18}O→ Sonika et. al., Phys. Rev. C **92, 024603 (2015)**

Experiment on fusion-barrier distribution

GPSC, CASCADE Hall

Quasi-elastic scattering measurement





Physics Letters B 845 (2023) 138120

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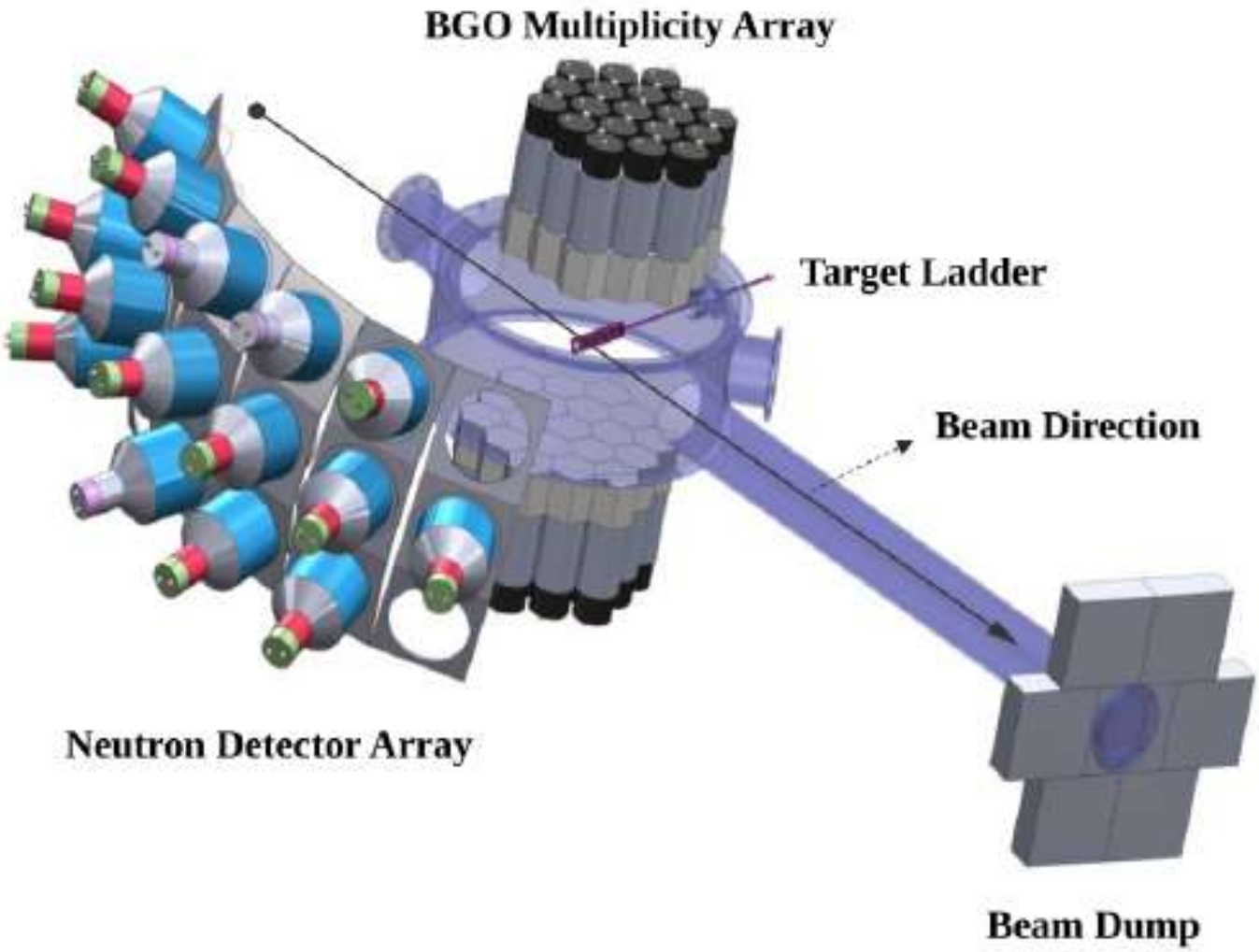
Precise determination of quadrupole and hexadecapole deformation parameters of the *sd*-shell nucleus, ^{28}Si

Y.K. Gupta[a,b,*], V.B. Katariya[c], G.K. Prajapati[a], K. Hagino[d], D. Patel[c], V. Ranga[e], U. Garg[f], L.S. Danu[a,b], A. Pal[a], B.N. Joshi[a], S. Dubey[g], V.V. Desai[g], S. Panwar[e], N. Kumar[a], S. Mukhopadhyay[a], Pawan Singh[a,b], N. Sirswal[a], R. Sariyal[h], I. Mazumdar[g], B.V. John[a]

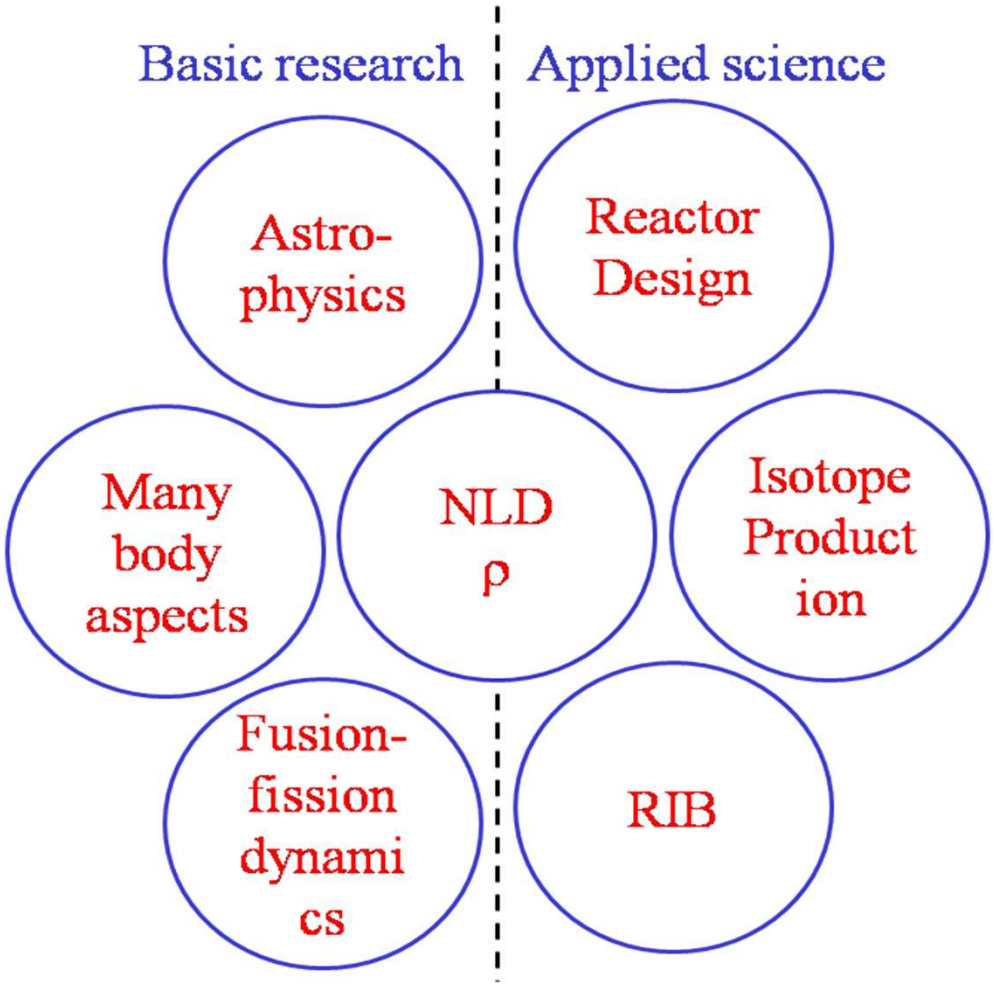
BARC-TIFR Pelletron-Linac facility

LINAC-HALL-1 (45 degree beam line)



Experiments on Nuclear Level Density

LINAC-HALL-1 (45 degree beam line)/Cascade Hall



$\rho(E_x) \sim e^{2\sqrt{(a\,E_x)}}$,

$a = \pi^2 g(\varepsilon)/6$, NLD parameter

ρ (A, E_x, J, parity, isospin, …)

Open problems in NLD

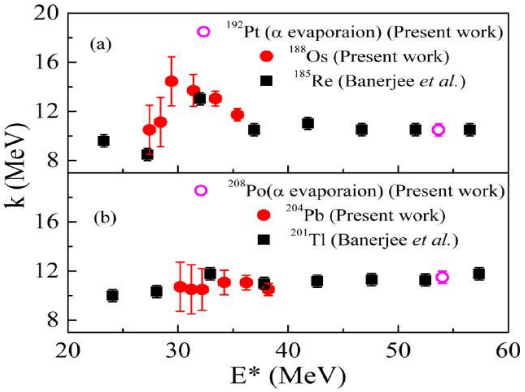
- Shell effect and its damping with Ex
- Rotational enhancement and its fade out with Ex
- Pairing re-entrance

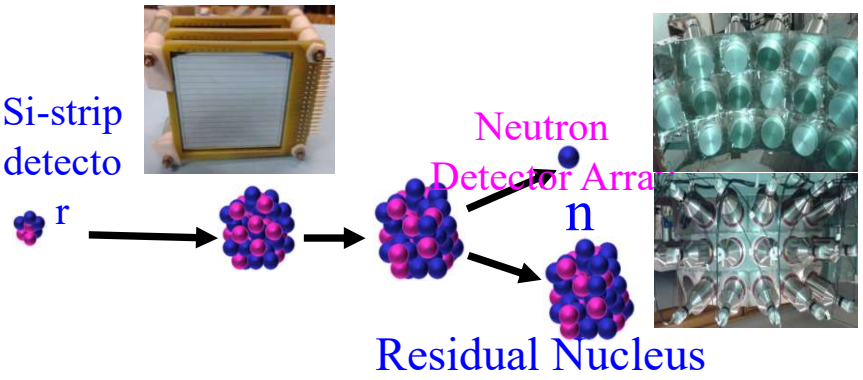
Experiments on Nuclear Level Density

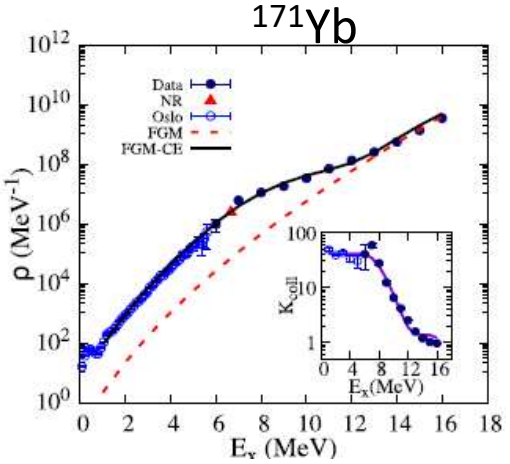
LINAC-HALL-1 (45 degree beam line)/Cascade Hall

Collective enhancement and its fade out with Ex

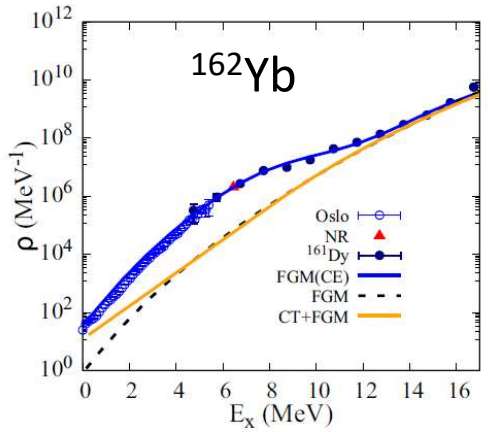
- Occurrence of collective rotational motion in atomic nuclei
- Implies a significant increase in the total NLD (Bjohnholm *et al. 1974).*
- Collective modes of excitation ($\rho = \rho_{int} K_{coll}$, Bohr & Mottelson
- Collective effect should disappear with Ex, $\rho = \rho_{int}$, Kcoll=1,
- Kcol=Krot*Kvib



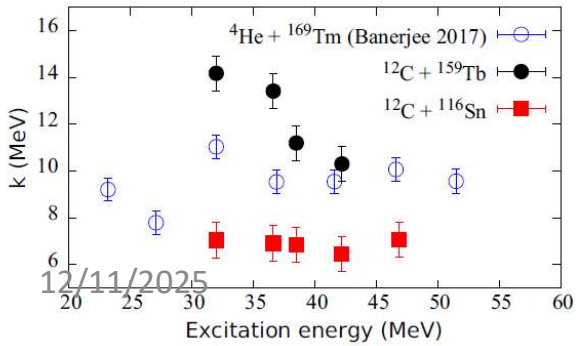




T. Santhosh et al.
PLB 841, 137934 (2023)



T. Santhosh et al.
PRC **108, 044317 (2023)**

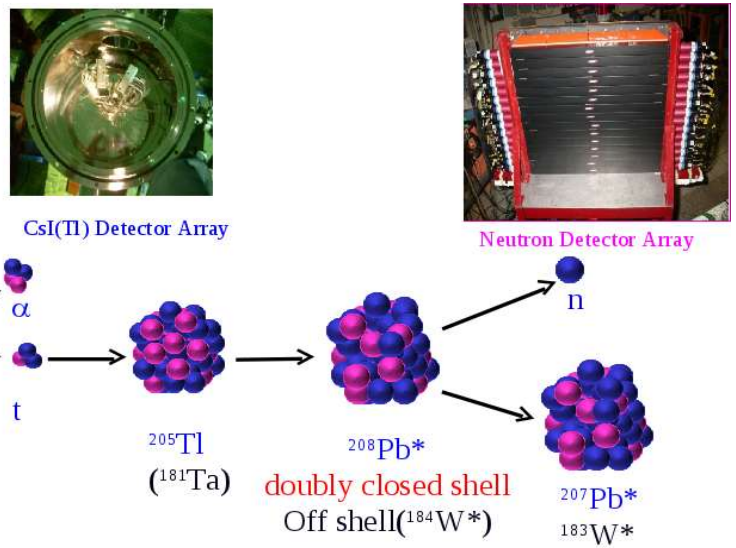


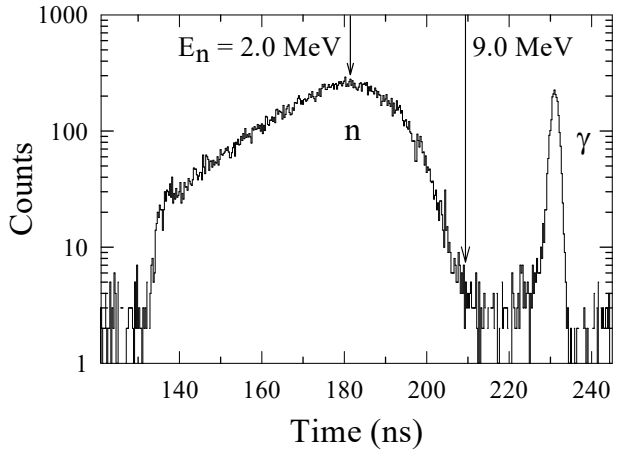
G. Mohanto et al. PRC **(2022), P. Taya et al. (under review)**

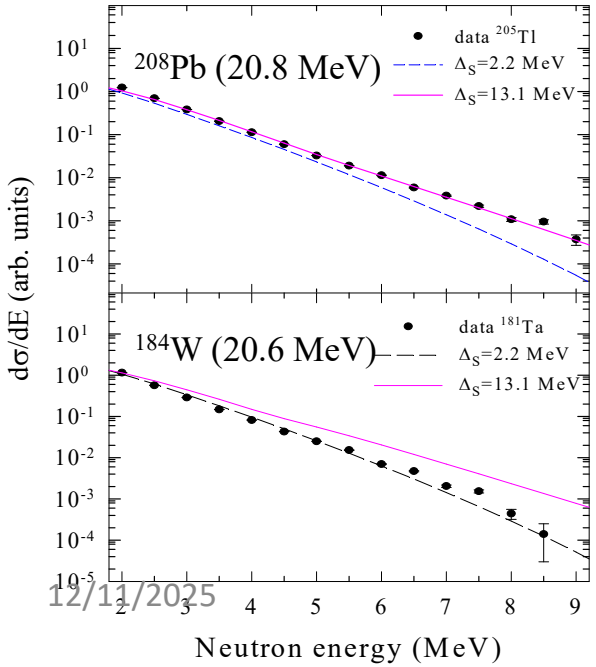
Experiments on Nuclear Level Density

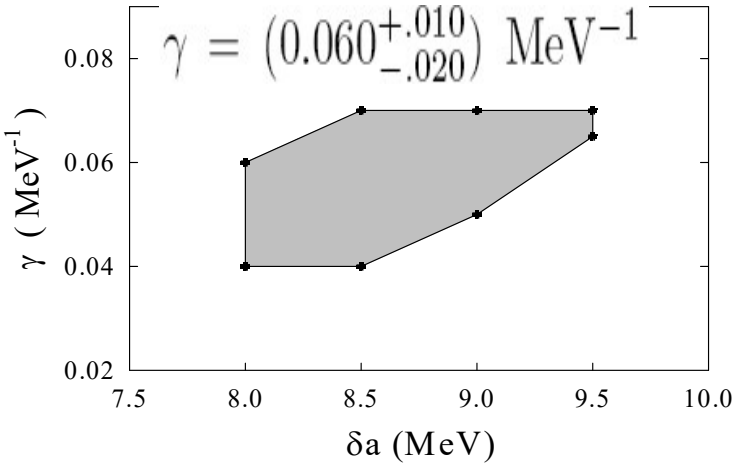
CASCADE Hall (15 degree beam line)

Nuclear Shell effect and its damping with excitation energy







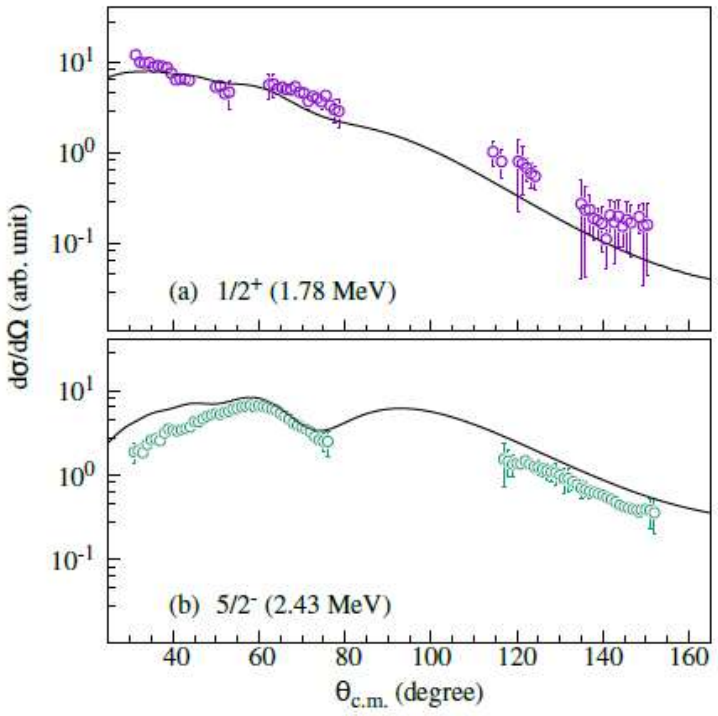


P C Rout et al, PRL 110, 062501 (2013)

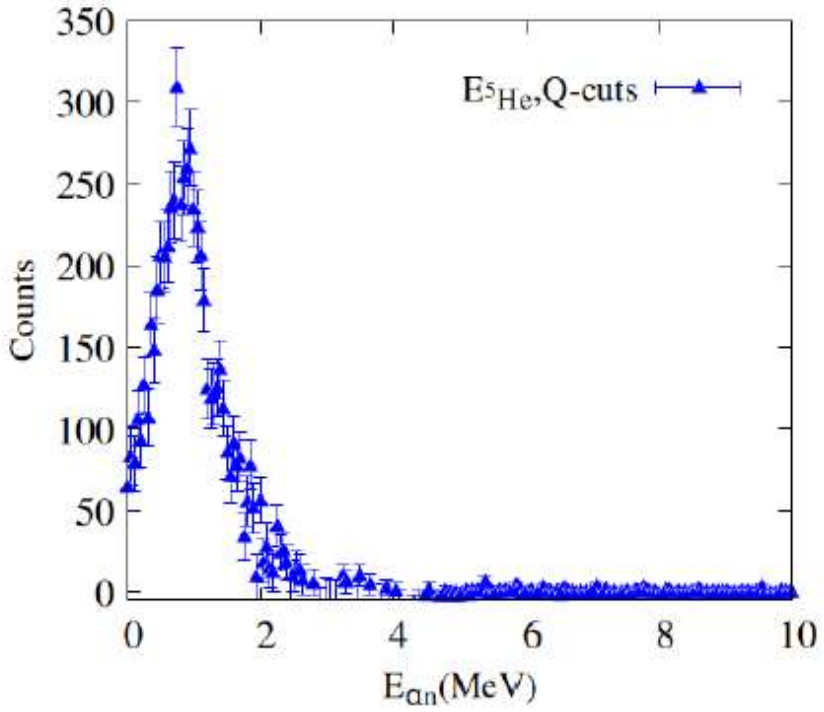
Experiments on breakup involving neutron

LINAC-HALL-1 (45 degree beam line)/Cascade Hall

$^{9}Be \rightarrow {}^{4}He + {}^{4}He + n$



$^{6}Li \rightarrow {}^{5}He \rightarrow {}^{4}He + n$



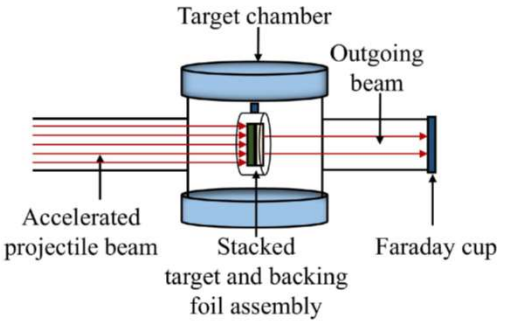
T. Singh et al. DAE-Symp on Nucl. Phys. (2025)

S.K.Pandit et al. DAE-Symp on Nucl. Phys. (2024)

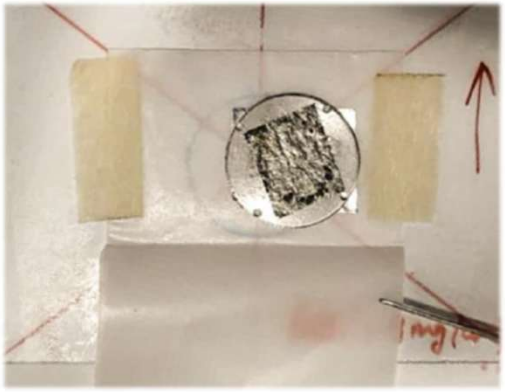
BARC-TIFR Pelletron-Linac facility

30 deg beamline, CASCADE Hall

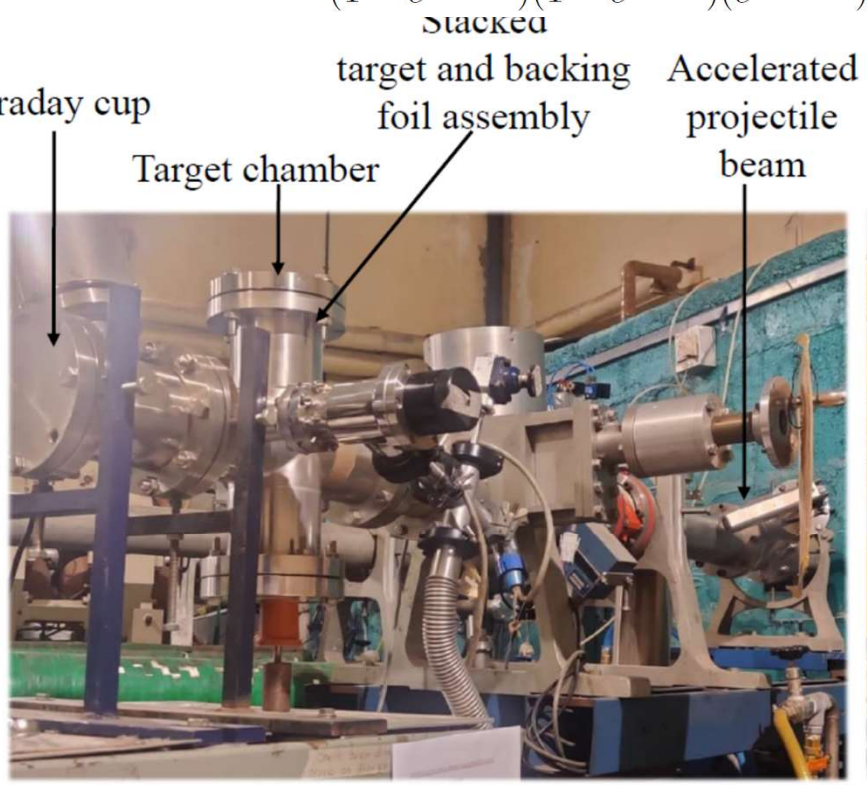
Offline γ-ray counting setup



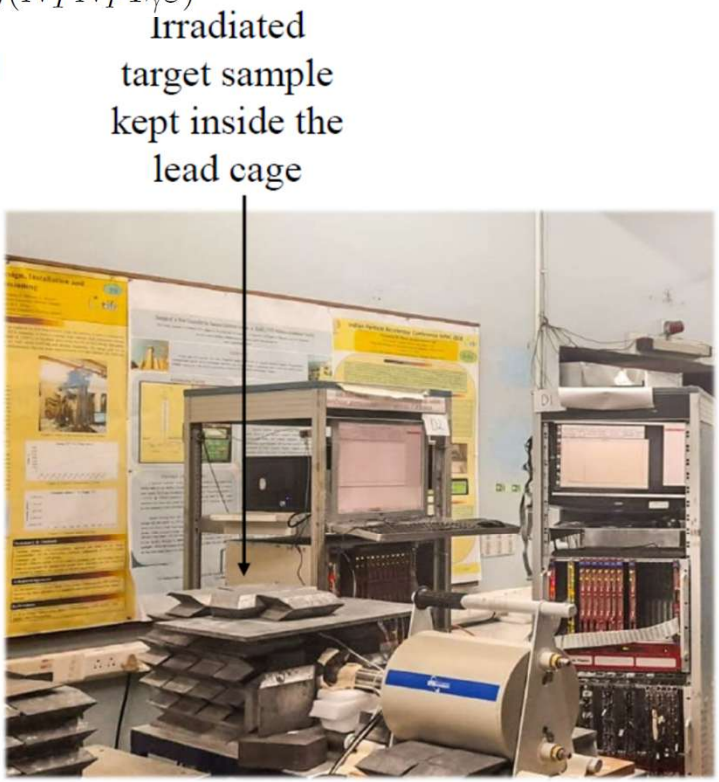
$$\sigma_R = \frac{Y\lambda}{(1-e^{-\lambda t_{irr}})(1-e^{-\lambda \Delta t})(e^{-\lambda t_{cool}})(N_T N_P I_\gamma \varepsilon)} \quad [2]$$



(a) Target sample



(b) Target Irradiation assembly

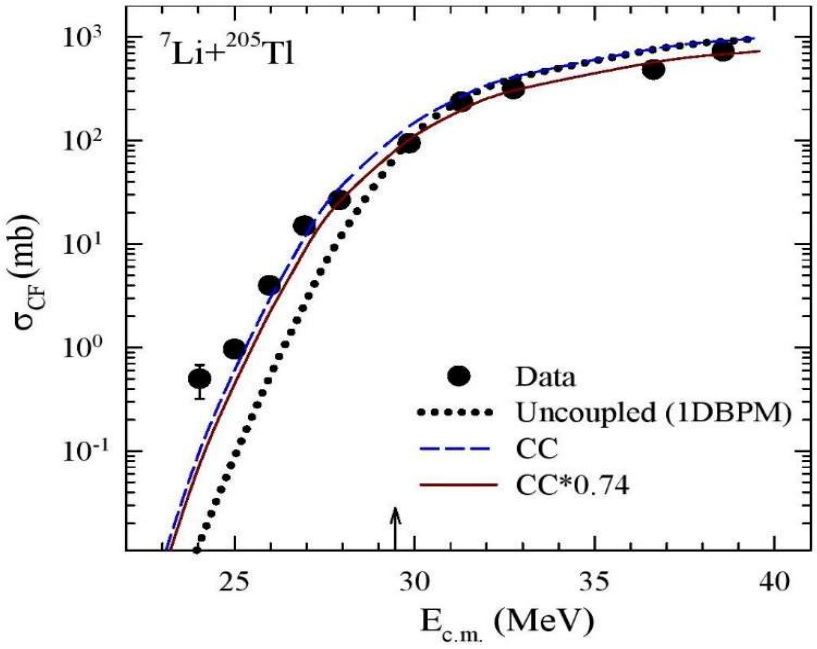


(c) Low background Offline γ- counting setup

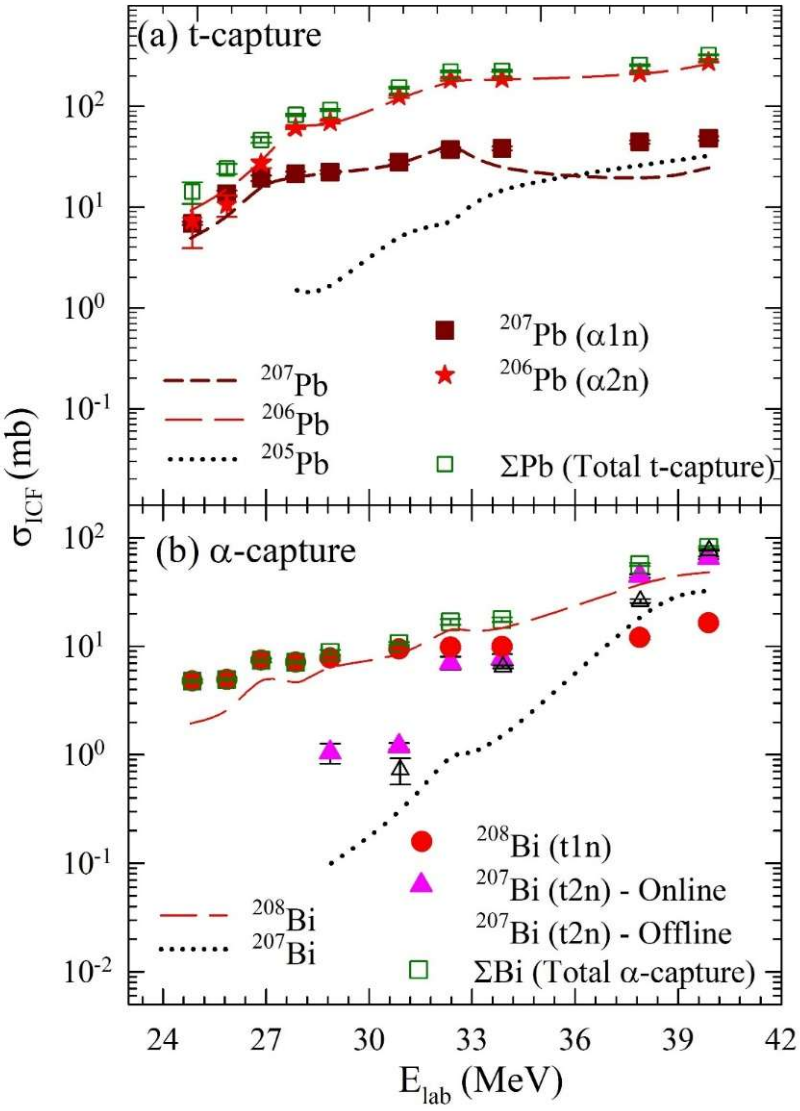
CF, ICF x-section measurements

30 deg beamline, CASCADE Hall

CF x-sections



ICF x-sections



Rath et al. PRC 79, 041601 (R)**(2009)**

Rath et al. PRC **88, 044617 (2013)**

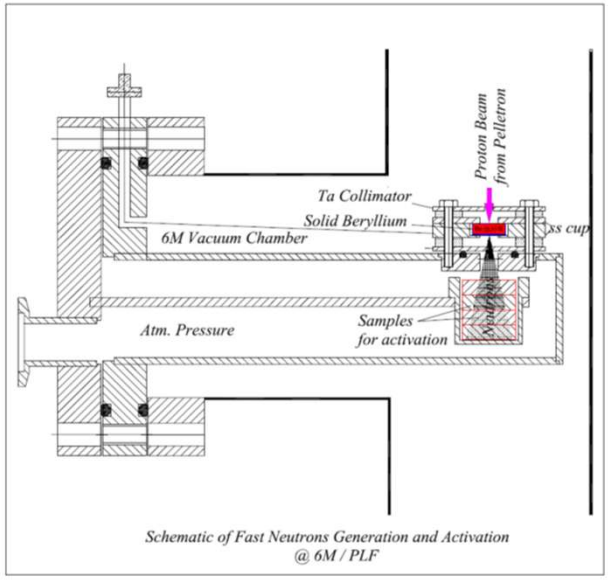
V. V. Parkar et al. PRC 97, 014607 (2018)

V. V. Parkar et al. PRC 98, 014601 (2018)

V. V. Parkar et al. PRC 109, 014610 (2024)

BARC-TIFR Pelletron-Linac facility

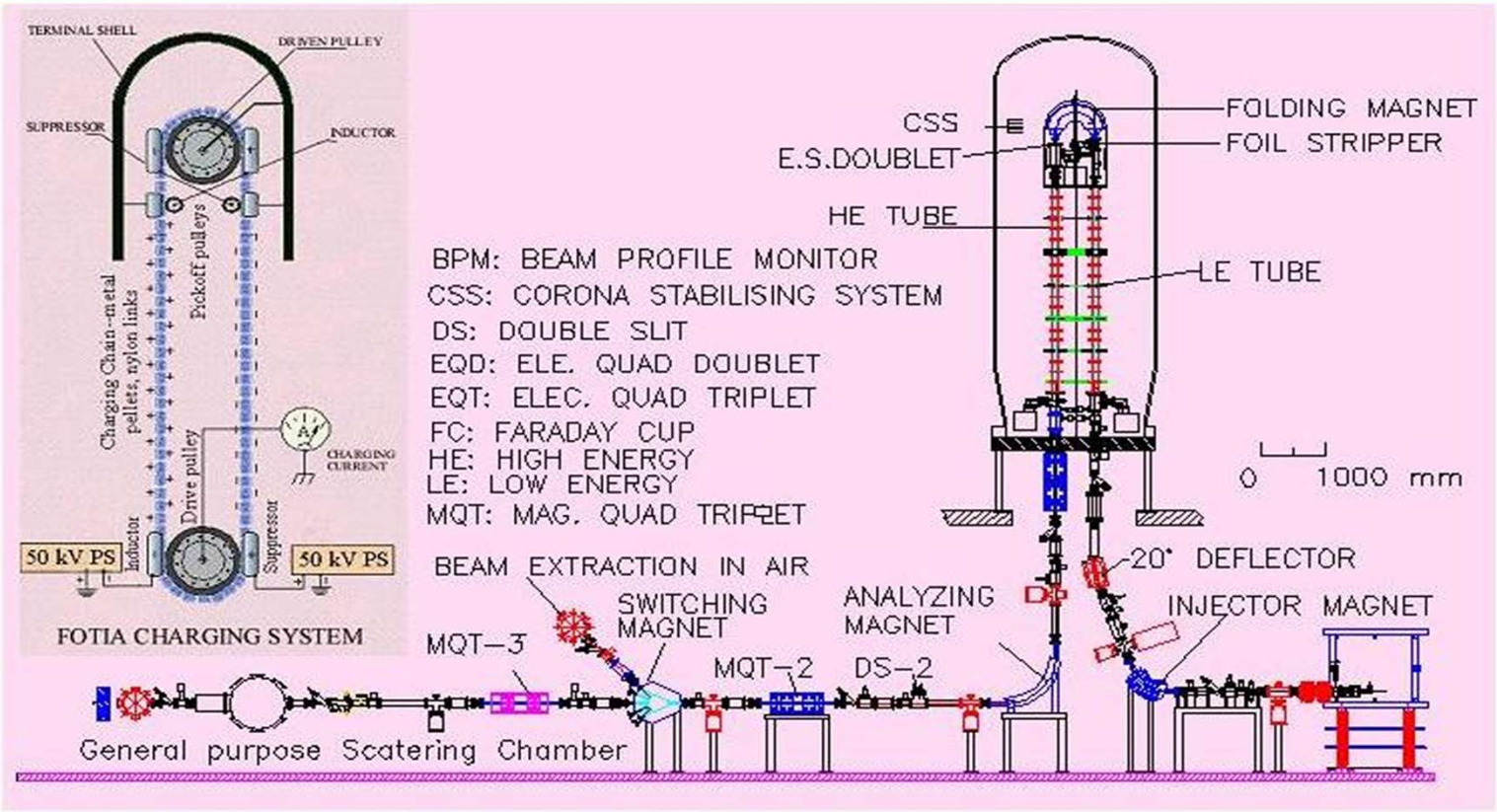
6M irradiation facility



- Beam – Proton
- Beam Energy- 4MeV to 22 MeV
- Nuclear Reactions-^{7}Li (p, n), ^{9}Be (p, n)
- Beam Current- 10 nA to 250 nA

- ❑ Corrosion studies for different structural materials
- ❑ Production of different radioisotopes such Ge-69,Re-186m etc

FOTIA facility, BARC

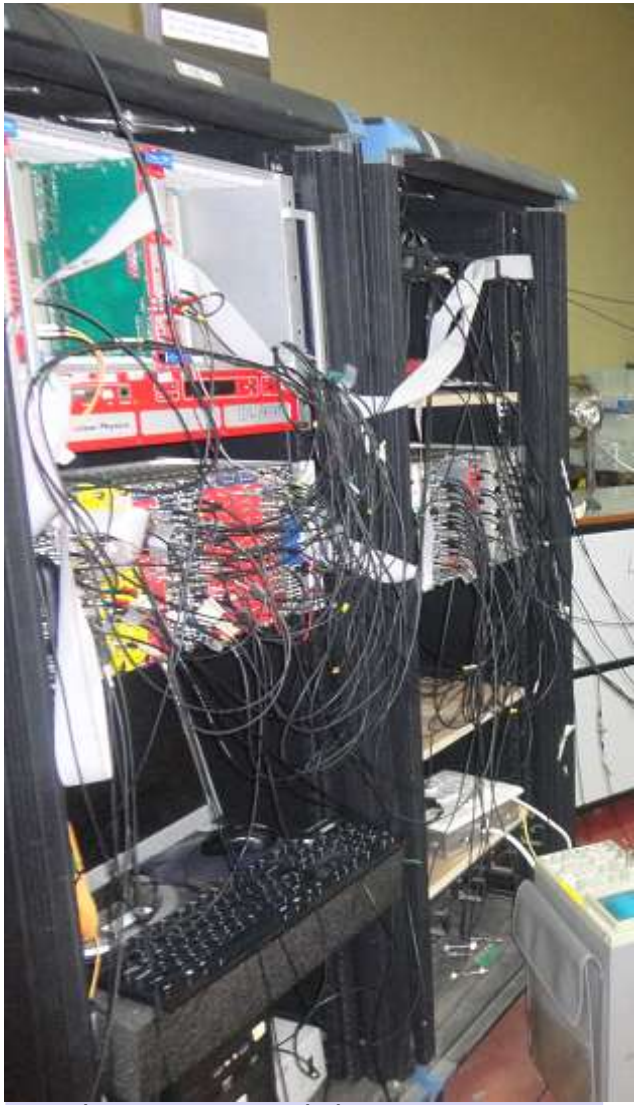


Terminal Voltage: 6 MV

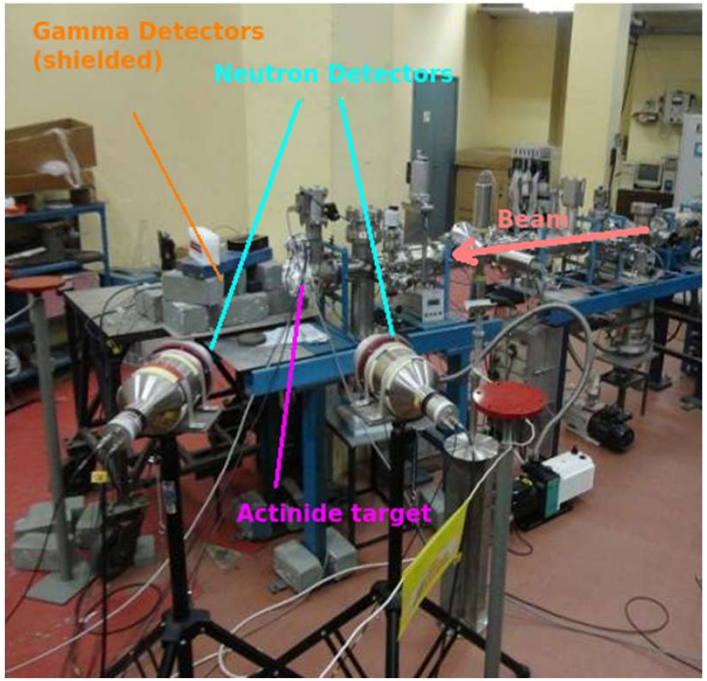
Beam: proton, alpha, lithium

Set up for Fission studies

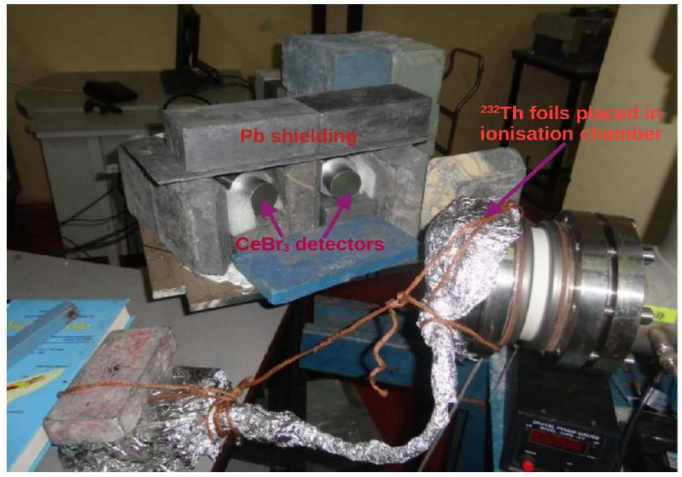
25 degree beam line, FOTIA



Electronics and data acquisition.



Detector set-up including Fission Chamber, Liquid Scintillation Detectors and $CeBr_3$ detectors.



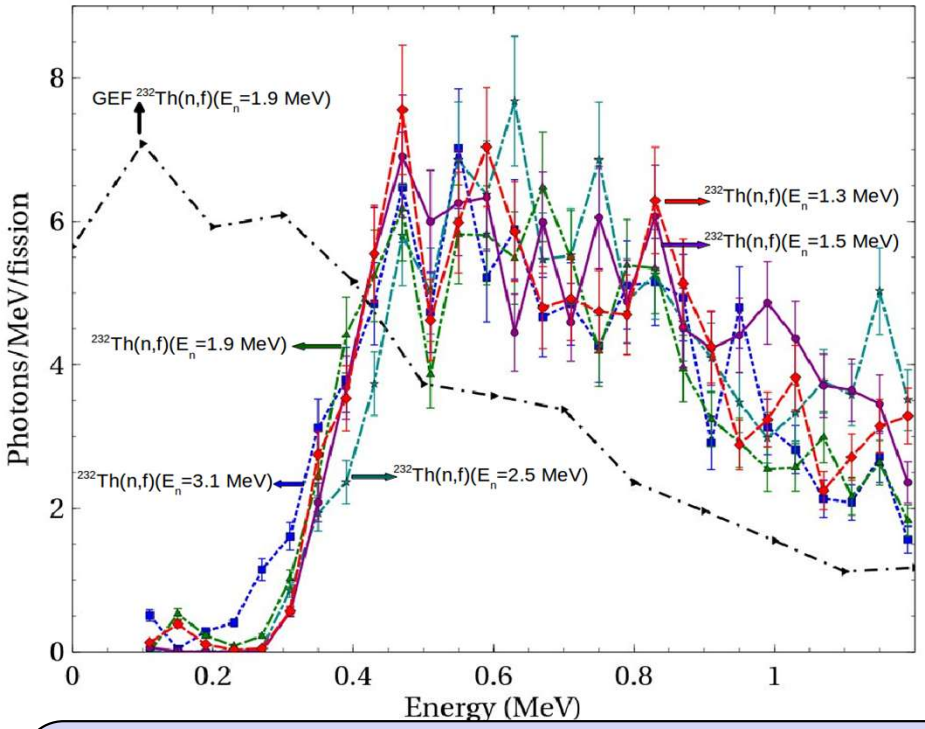
Close-up view of Fission Chamber, and the lead shielded $CeBr_3$ detectors.

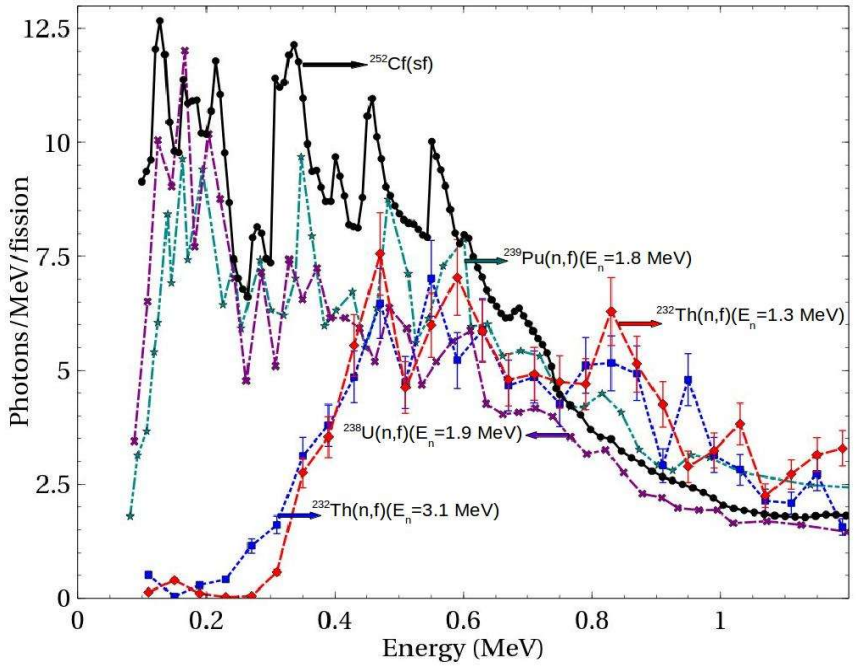
Courtesy: Dr. R.G.Thomas

Fission research

25 degree beam line, FOTIA

Intriguing features of the prompt fission γ-ray spectra in the fast neutron induced fission of ^{232}Th





- Total energy carried by the γ-rays/fission in ^{232}Th(n,f) is found to be ~40-50% higher than the predictions of the existing models.
- Important in the calculation of gamma heating in reactor systems that use ^{232}Th.

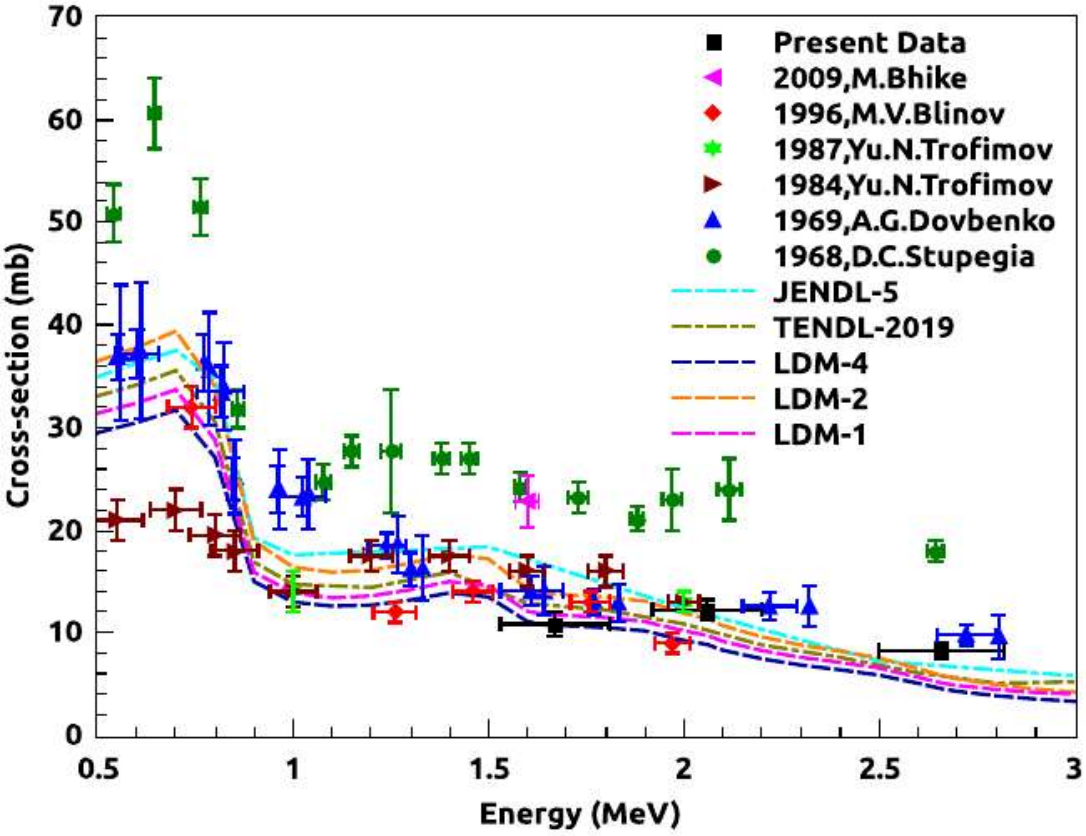
Sukanya De, R. G. Thomas, G. Mishra, G. Mohanto, Ajay Kumar, Eur. Phys. J. A 61 (2025) 38

Courtesy: Dr. R.G.Thomas

(n,γ) x-section

25 degree beam line, FOTIA

- Molybdenum is a critical material to be used in fusion reactors like the ITER due to its resistance to high temperature, pressure and corrosion.
- Experimental cross-section data for this reaction are available in the EXFOR data library but none of the data include a detailed covariance analysis.



^{98}Mo(n,γ)^{99}Mo cross-sections measured in the present experiment with associated uncertainties and correlation coefficients.

$\langle E_n \rangle$ (MeV)	Present data (mb) ($\sigma \pm \Delta\sigma$)	Correlation matrix		
1.67 ± 0.14	10.8476 ± 1.1544	1.0000		
2.06 ± 0.14	12.2408 ± 0.9994	0.1503	1.0000	
2.66 ± 0.16	8.2430 ± 0.7168	0.1163	0.1587	1.0000

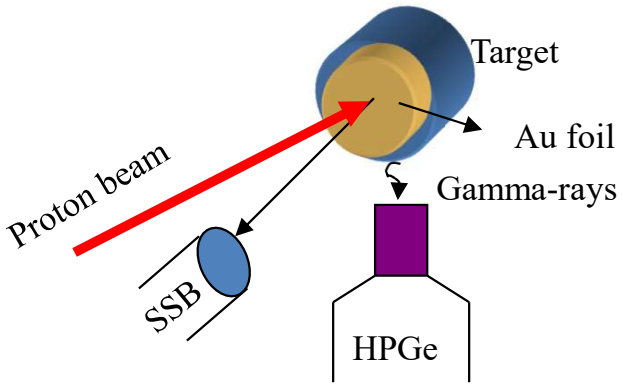
Mahima Upadhyay et al., **J. Phys. G: Nucl. Part. Phys. 50 (2023) 125107 (16pp)**

Courtesy: Dr. R.G.Thomas

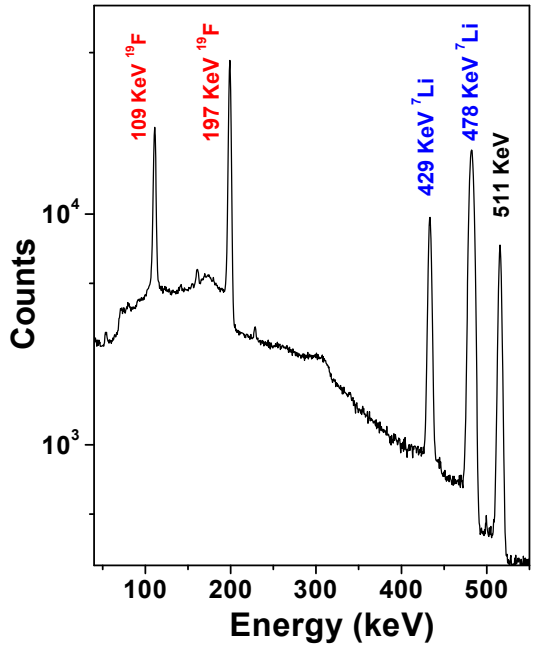
Proton Induced Gamma Emission

-25 degree beam line, FOTIA

- Possible nuclear reactions, (p,γ), (p,p'γ), (p,αγ), etc. using proton beam from FOTIA
- Analytical technique, good for determining isotopic compositions, particularly for low Z elements, complementary to PIXE



Element	Reaction	Eγ (keV)
Li	^{7}Li (p, p' γ) ^{7}Li ^{7}Li (p, n γ) ^{7}Be ^{6}Li (p, γ) ^{7}Be	478 429 429
F	^{19}F (p, p'γ) ^{19}F ^{19}F (p, p'γ) ^{19}F	110 197



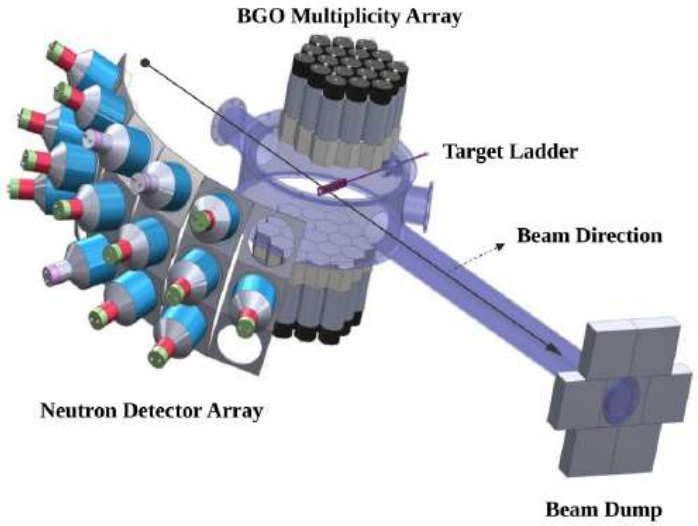
Advantages

- Simultaneous multi-elemental determination
- Complementary to NAA, PIXE & XRF
- Often solid sample for analysis – thus non-destructive

User: Dr. R. Achariya, RCD, BARC

Future upgradations

- Scattering Chamber of 45deg, Hall1 to be modified→ MWPC detectors can be mounted



- VME based data acquisition to be replaced by Digital data acquisition

- Windowless gas target to be installed in Cascade Hall

Summary

- Various experimental facilities have been shown
- Different types of experiments on fission discussed
- Experiments involving charge particle detector array discussed
- Experiments with neutron/gamma detectors array discussed

Acknowledgement

- BARC-TIFR colleagues

Collaborators

IIT Roorkee

Andhra University

VECC

BHU

University Of Calicut

THANKS FOR YOUR KIND ATTENTION